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Thermophysical Properties for ASK Chemical and Exochem Riser Sleeves for Steel Castings

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Abstract

In order to predict the performance of a riser sleeve using simulation software, the thermophysical properties of that sleeve must be known. Current literature gives little to no information about these properties. Some manufacturers have given these properties as an optional module for simulation software without revealing their actual values. The accuracy of these "black box" properties is uncertain. In this paper, progress in determining these properties is detailed. In particular, properties are developed for five unique sleeves from two separate manufacturers, Exochem and ASK Chemicals. According to the manufacturers' information, two sleeves are said to be insulating and three sleeves are exothermic. Temperature dependent sleeve properties such as the thermal conductivity and the specific heat are determined by matching casting simulation results to results from casting experiments. Exothermic properties such as ignition temperature, burn time, and heat generation are determined in the same manner. Once the thermophysical properties of these riser sleeves have been determined, the sleeves are compared on the basis of heat diffusivity, the product of density, specific heat, and thermal conductivity.

I. Introduction

Riser sleeves have been used for many years to improve casting yield by minimizing the size of risers. Each year U.S. casting companies spend millions of dollars on these riser sleeves yet there is little consensus or information regarding proper usage of the sleeves and how to predict their performance. Determining the thermophysical properties of these sleeves will allow for accurate predictions of performance using simulation software. This will allow foundries to minimize the number and sizes of risers in their casting processes. Smaller risers and riser contacts will also result in lower cleaning room costs. Additionally, using accurate sleeve properties and simulation, guidelines can be developed on proper sleeve usage. Currently there are no clear guidelines on when foundry engineers should use insulating or exothermic sleeves. The Steel Founder's Society of America (SFSA) estimates that adoption of such guidelines would save foundries millions of dollars by allowing them to pour less metal and to make more educated choices on sleeve selection.

Very little open information is known about the thermophysical properties of riser sleeves. This presents difficulties when using sleeves in casting simulation software. Some manufacturers, such as FOSECO and ASK Chemicals, provide the necessary temperature dependent thermophysical property data that is required for simulation. Unfortunately this data is presented as an optional module in the simulation software *MAGMAsoft* and the properties themselves are not disclosed to the software user. Therefore, the properties are provided as a "black box" database where the user selects a sleeve type and the properties are applied during simulation. The accuracy of these black box properties is unknown. In addition, previous studies have shown little difference between an insulating sleeve and an exothermic sleeve [1], which points out the uncertainties on when to use different sleeve types..

This paper details the work on developing thermophysical properties for five different riser sleeves. These sleeves are produced by Exochem (ESPX, SNA and ES) and ASK Chemicals (EX and IN). Three sleeves are exothermic while the other two are insulating. According to a survey of SFSA members, sleeve usage is shown in Figure 1. Note that these five sleeves make up approximately 25% of industry usage.

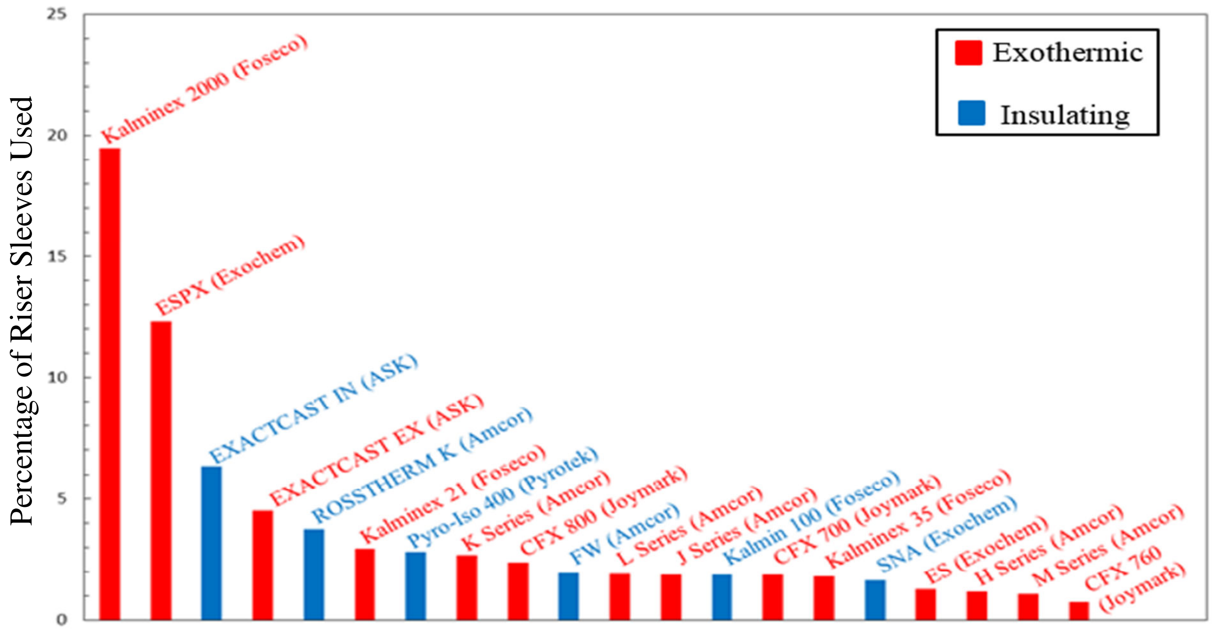


Figure 1. Riser sleeve products and manufacturers ranked by popularity of use by SFSA members.

II. Casting Experiments

Casting experiments were performed to collect thermocouple (TC) temperature data which was used along with casting simulation to determine the sleeve thermophysical properties. In this process, the sleeve thermophysical property data used in casting simulations was adjusted iteratively through trial and error until the best possible agreement was obtained between the measured and predicted temperatures throughout the casting solidification process. Locations of the temperature measurements were in the casting, mold and sleeve. The casting experiments were performed at the University of Northern Iowa Metal Casting Center. The temperature history data (temperature vs. time) at each TC location was recorded through the casting process until the casting cooled to room temperature. For each set of casting experiments, a control casting experiment without a sleeve was performed in addition to the sleeved casting experiments.

Side and top views of a control experimental casting setup are shown in Figure 2a, and these views are shown in Figure 2b for a sleeve experimental casting setup. The control and sleeve experiments are cylindrical castings, essentially just a riser as seen in Figure 2. A pouring cup and sprue, and a lid (the cope) was used to minimize heat loss to the atmosphere. The control casting (no sleeve casting) TC data was used to determine the best simulation sand and

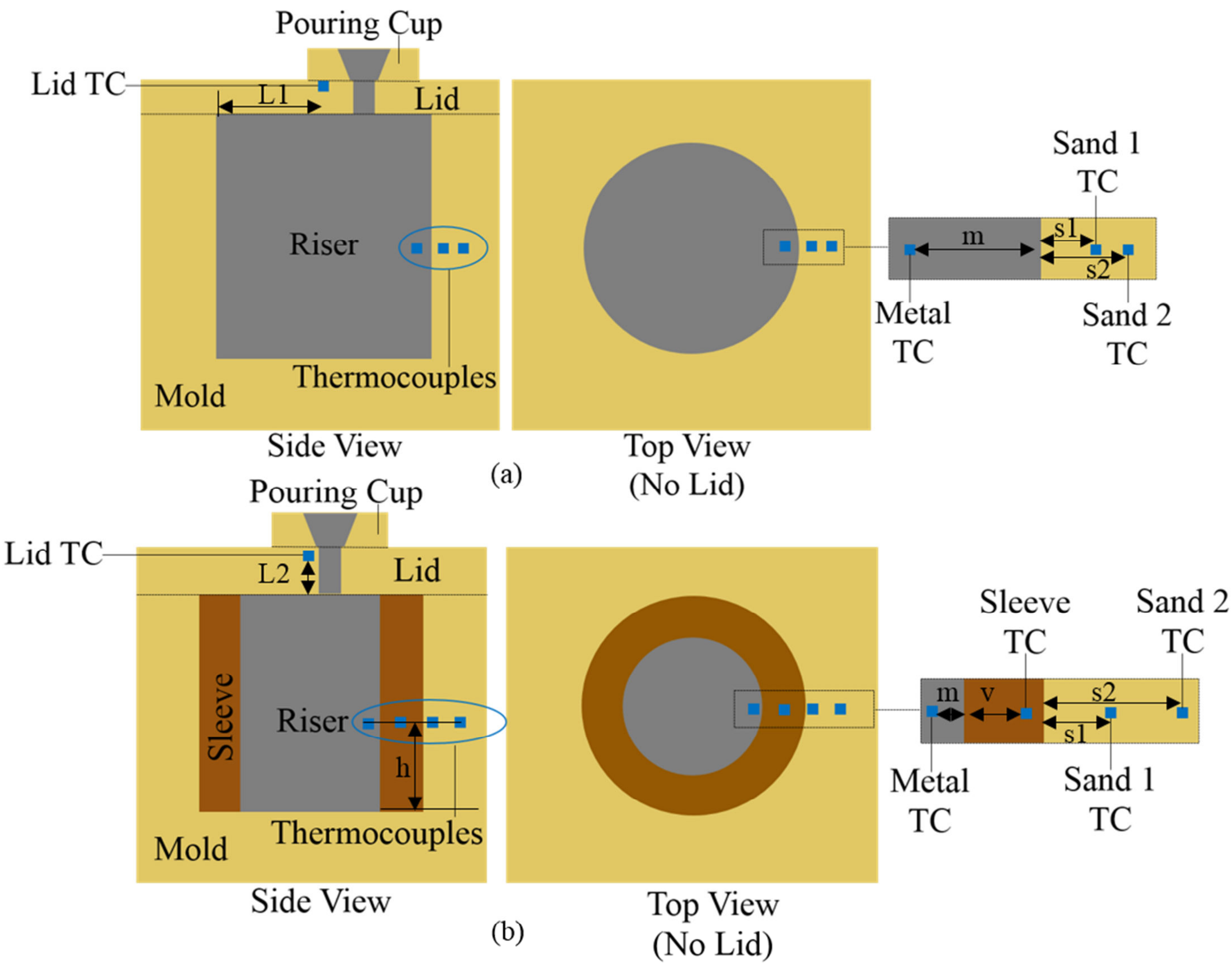


Figure 2. Experimental setup for a) the no sleeve castings and b) the sleeve castings. Dimensions indicated in the figure correspond to those given in Table IIa and IIb.

steel thermophysical properties in the simulation. These steel and sand properties were determined by iteratively comparing simulated TC data to the measured data until the best possible agreement was found. In each casting experiment for a given sleeve type, two sleeve castings were always poured to provide a measure of variability in the casting experiments.

The casting molds were made from 55 micron silica sand using Pepset PUNB binder. The molds used in these experiments had a 9" x 10" rectangular base and 9" height. The mold lid had the same dimensions as the rectangular base of the mold but with a height of 2”. The bottom of the sprue was designed to be tangentially flush with the outer edge of the cylindrical

Table I. Sleeves used in these experiments. Sleeve dimensions and dimensions for the corresponding control casting are included.

Sleeve Measurements							
Manufacturer	Sleeve (I/E)	Sleeve Inner Diameter	Sleeve Thickness	Density (kg/m^3)	Sleeve Height	Control Casting Diameter	Control Casting Height
Exochem	ES (E)	3”	1.25”	676	6”	3”	5”
	ESPX (E)	3”	0.5”	531	5”	3”	5”
	SNA (I)	6”	0.5”	479	6”	6”	6”
ASK	Exactcast EX (E)	4”	0.5”	529	6”	4.5”	6”
	Exactcast IN (I)	4.25”	0.375”	395	6”	4.5”	6”

casting. The sleeves tested in these experiments are listed in Table I along with the dimensions of the no sleeve (control) casting used to determine steel and sand simulation properties for that sleeve experiment.

Type-B thermocouples sheathed in a quartz tube were placed in the metal and the sleeve. The metal thermocouples were located as close to the center of the casting as possible. The TCs in the metal were inserted horizontally from the “back” of the casting. Type-K TCs were placed at locations in the sand mold. Thermocouples placed in the sand and sleeve were inserted downwards through the lid. Thermocouple locations are given in Tables II and III. The radial location of the metal TC from the mold-metal interface is m. The radial location of the sleeve TC from the sleeve-metal interface is v. The radial locations of the sand TCs measured from either the mold-metal or sleeve-metal interface (depending on whether the casting is using a sleeve) are denoted by s1 and s2. The vertical location of the sand, sleeve, and metal TCs are

Table II. Thermocouple locations for the no sleeve "control" castings. Castings are labeled according to their corresponding sleeve castings. Note that two metal thermocouples were placed in each control casting

No Sleeve Casting Thermocouple Locations					
Casting	m, h	s1, h	s2, h	L1	L2
SNA	1”, 3”	6 mm, 3”	18 mm, 3”	5”	1”
	0.75”, 3”				
ESPX	1”, 2.5”	6 mm, 2”	18 mm, 2”	5”	1”
	1”, 1.5”				
ES	1.5”, 0.5”	6 mm, 2”	18 mm, 2”	5”	1”
	1”, 2.5”				
ASK EX	1.125”, 3”	6 mm, 3”	18 mm, 4.5”	5”	1”
	1.125”, 2”				
ASK IN	0.75”, 4”	6 mm, 2.75”	18 mm, 3”	5”	1”
	1.75”, 2”				

referenced from the bottom of the cylindrical cavity and are dented by h. Finally the horizontal and vertical locations of the lid TCs, L1 and L2 respectively, are measured from the "back" edge of the lid and bottom of the lid, respectively. The metal poured in all experiments was plain carbon steel. The chemistries poured in four of the five sleeve experiments are given in Table IV and the steel chemistry pour for the ASK IN experiment was unavailable for this paper.

Table III. Thermocouple locations for sleeve castings where 1 and 2 denote different castings.

Sleeve Casting Thermocouple Locations						
Casting	m, h	v, h	s1, h	s2, h	L1	L2
SNA 1	1.125", 3"	9 mm, 3"	6 mm, 4"	18 mm, 3"	5"	1"
SNA 2	1.25", 3"	9 mm, 3"	6 mm, 3.75"	18 mm, 3"	5"	1"
ESPX 1	1", 2"	6 mm, 2.5"	6 mm, 2.5"	18 mm, 2.5"	5"	1"
ESPX 2	1", 2"	6 mm, 2.5"	6 mm, 2.5"	18 mm, 2.5"	5"	1"
ES 1	0.5", 2"	12 mm, 3"	1 mm, 3"	10 mm, 3"	5"	1"
ES 2	1.375", 2"	12 mm, 3"	1 mm, 3"	10 mm, 3"	5"	0.75"
ASK EX 1	1.125", 3"	6 mm, 4"	6 mm, 3"	18 mm, 4.5"	5"	1"
ASK EX 2	1.125", 3"	6 mm, 4.5"	6 mm, 4.5"	18 mm, 4.5"	5"	1"
ASK IN 1	1.75", 3"	6 mm, 4.875"	8 mm, 4.5"	20 mm, 4"	5"	1"
ASK IN 2	1.75", 3"	6 mm, 4.375"	8 mm, 4"	20 mm, 4.5"	5"	1"

Table IV. Chemistries cast in the experiments labeled according to the sleeve and control castings they correspond to. The ASK IN chemistry is currently unavailable.

Casting Chemistries (%)								
	C	Si	Mn	Cr	Mo	Cu	Sn	Fe
SNA	0..22	0.60	0.49	0.16	0.16	0.2	0.21	97.98
ESPX	0.27	0.52	0.55	0.24	0.07	0.2	0.02	97.92
ES	0.28	0.5	0.56	0.09	0.05	0.14	0.013	98.10
ASK EX	0.31	0.56	0.54	0.18	0.01	0.14	0.01	98.05

III. Experimental Results for Similar Sized Control and Sleeved Castings

Results for the casting experiments are presented below. Results presented here focus on the steel temperatures as they provide a clear measure of a sleeve's performance. The control casting diameters for the cases presented below can be found in Table I. The control casting sizes were designed to be similar in size to the sleeve castings making the experimental results with and without sleeve comparable. It is clear from these charts that all sleeves have a beneficial effect on extending the solidification times for a given casting. Of particular interest note in Figure 3b where the insulating sleeve outperforms the exothermic sleeve based on the time the casting takes to reach solidus. This follows with a previous finding [1] that insulating sleeves can perform as well as or better than exothermic sleeves.

IV. Experimental and Simulation Results for Control Castings

As mentioned earlier, each set of experiments is cast with a "control" casting. This casting had no sleeve. It allows for the determination of sand and steel thermophysical properties without influence from the riser sleeve. Through the numerous experiments performed here, it was found that the sand and steel properties do not vary greatly when simulating different experiments and comparing their predicted and measured temperatures. It was found that heat-to-heat differences in the steel poured can be accounted for by modifying the solid fraction curves for the steel and the thermal conductivity for the sand. Additionally, there are slight modifications to the thermal conductivity and the density of the steel. All properties used for the control cases are listed in Appendix A. Results of simulations using these properties are shown in Figures 4 to 8 and are compared to measurements. Each figure corresponds to the control casting experiment for one sleeve. In all figures black curves are simulated temperatures while red curves are measured experimental data. These figures show excellent agreement between measured and simulated steel temperatures. Agreement between sand and lid experimental and simulated temperatures is good. Once agreement between predicted and measured temperatures was established for a control case, the steel and sand thermophysical properties for that set of casting experiments were set. They were not modified again in the process of determining the sleeve thermophysical properties. Therefore, the same mold and steel properties from the control case were used in the iterative simulations run to determine sleeve properties. When determining the sleeve properties, only properties related to the sleeve were modified iteratively until the best possible agreement was obtained between predicted and measured sleeve experimental temperatures.

V. Experimental and Simulation Results for Sleeve Castings

After determining the sand and steel properties from the control experiments, the sleeve properties were determined. In the process of determining the sleeve thermophysical properties the temperature dependent sleeve density, specific heat and thermal conductivity in simulations were adjusted through iterative simulations to achieve agreement between the measured and simulated temperatures over time for the sleeve experiments. The sleeve property data were assumed to fall within reasonable limits, and no unreasonable property values were used to force the agreement of the simulations with the measurements. The final sleeve properties reported

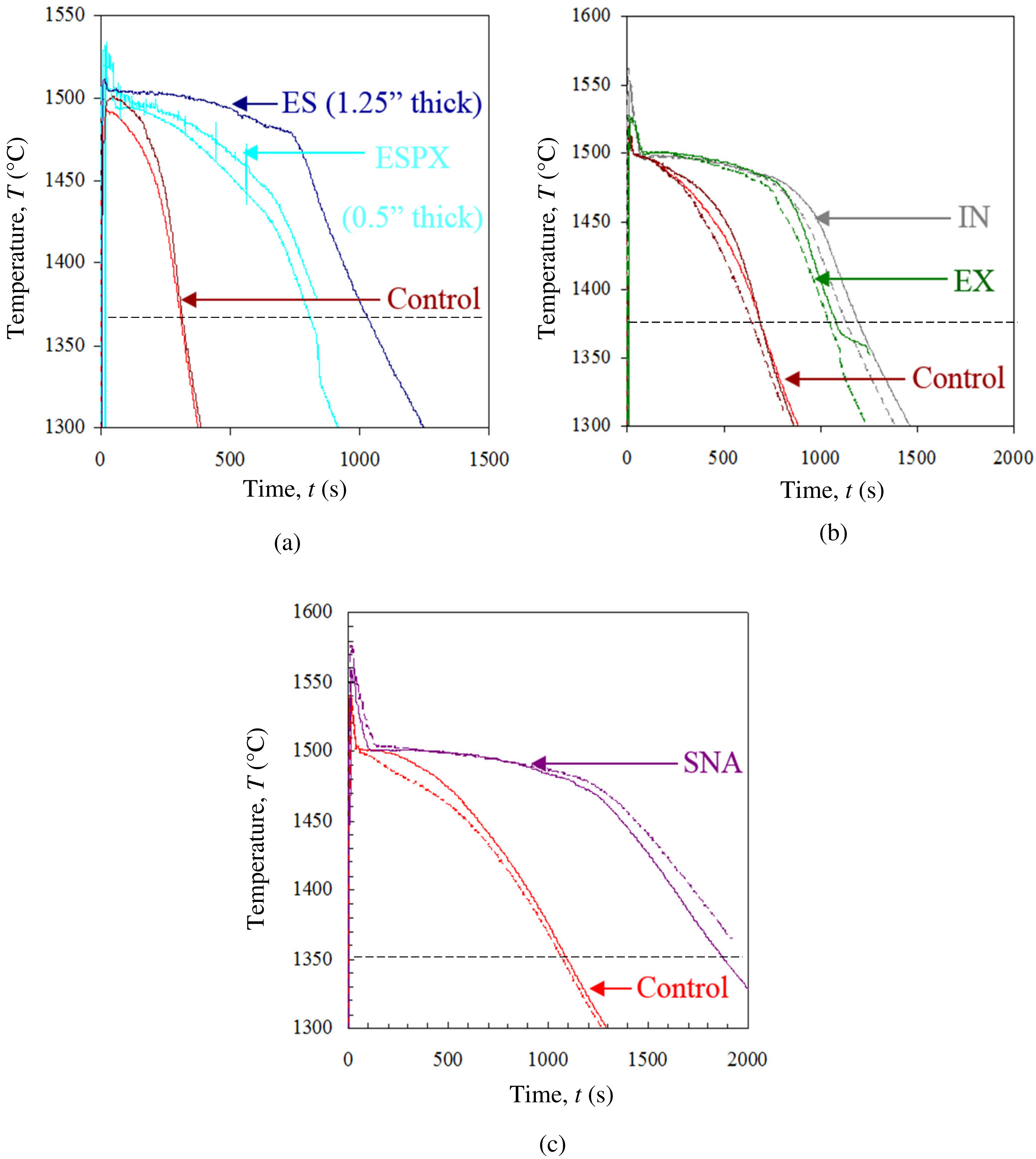


Figure 3. Temperatures measured in casting experiments for a) 3" diameter castings, note a difference in thickness between ES and ESPX; b) 4" diameter castings, note that the control has a diameter of 4.5" and IN has a diameter of 4.25"; c) 6" diameter castings; Dark and bright red curves are separate control castings. Solidus temperature is indicated by a dashed black line.

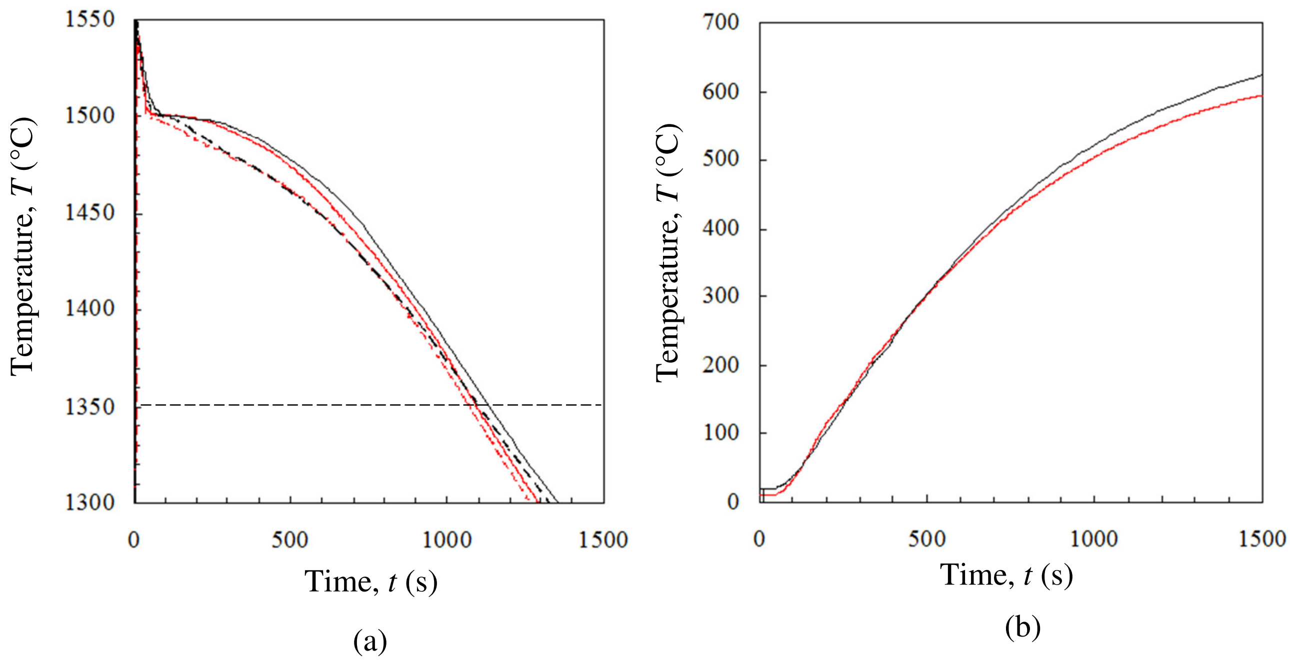
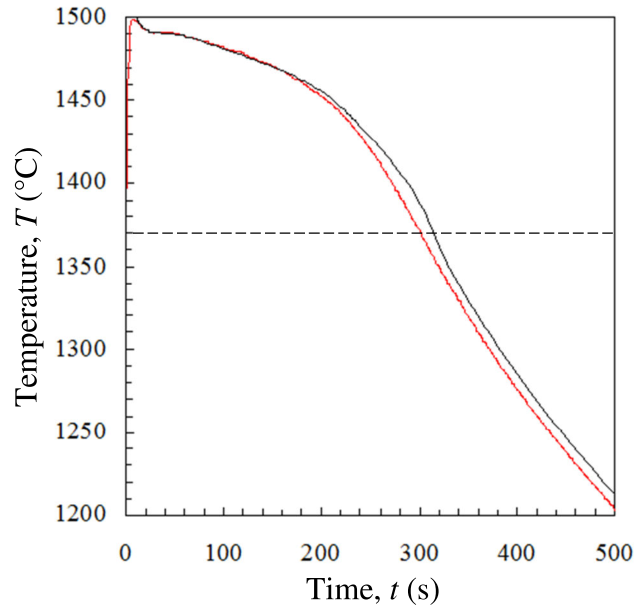


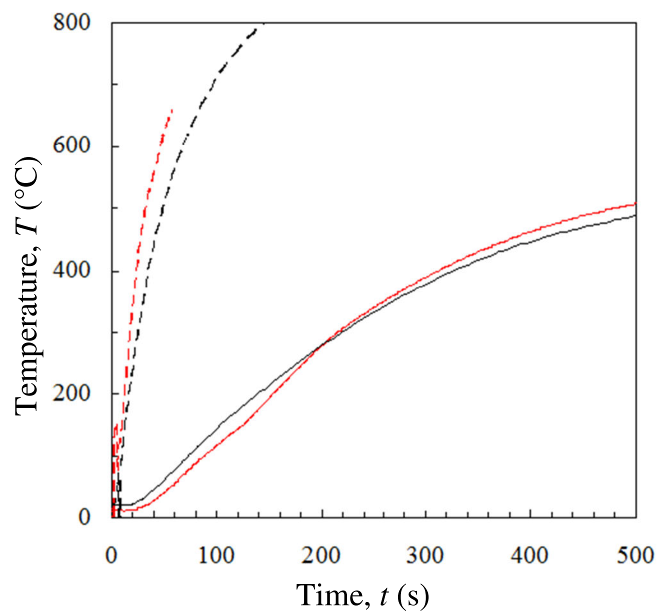
Figure 4. Simulation (black) compared to measured (red) results for the SNA control casting. (a) Steel temperatures. Solidus temperature is indicated by a horizontal black line. (b) Lid temperatures. Sand thermocouples were destroyed by flash between the cope and drag.

here produced the best agreement found between the measured and predicted temperatures. The number of iterative simulations required to determine a good set of sleeve properties varied from about 50 to over 100 simulation runs using the casting simulation software *MAGMAsoft*.

Once the sleeve properties are determined, this allows the calculation of a temperature dependent heat diffusivity, which the authors propose as a representative property for comparing one sleeve to another, and for comparing sleeves to the sand mold as well. Heat diffusivity is the product of the thermal conductivity, k, the density, ρ, and the specific heat capacity, c_p. Additionally, exothermic sleeves require specification of an ignition temperature, a burn time, and a heat release per unit mass. In order to simplify the determination of the sleeve properties, the density is held constant, equal to the measured room temperature density. This density is listed in Table I. In reality, the sleeve density decreases at high temperatures due to burning off of its constituents. After performing many simulations the specific heat of the sleeve was found to have a low sensitivity in the simulations. This is because any change to the specific heat is believed to be less than a factor of 2. As a result, only the thermal conductivity values for the sleeve were varied in determining the sleeve properties that gave good agreement with the measured temperatures. In the case of exothermic sleeves, the exothermic properties must also be determined. The heat diffusivities for all sleeves determined by the process described here can be found in Figure 9. Bear in mind that the exothermic properties of the sleeve are not reflected in the heat diffusivity comparisons. It is proposed that in the absence of exothermic properties, the heat diffusivity provides a means for comparing sleeve material performance; the low the heat diffusivity the better the sleeve material. However, comparing the heat diffusivities is not equivalent to comparing sleeves of a given geometry, as it does not consider sleeve

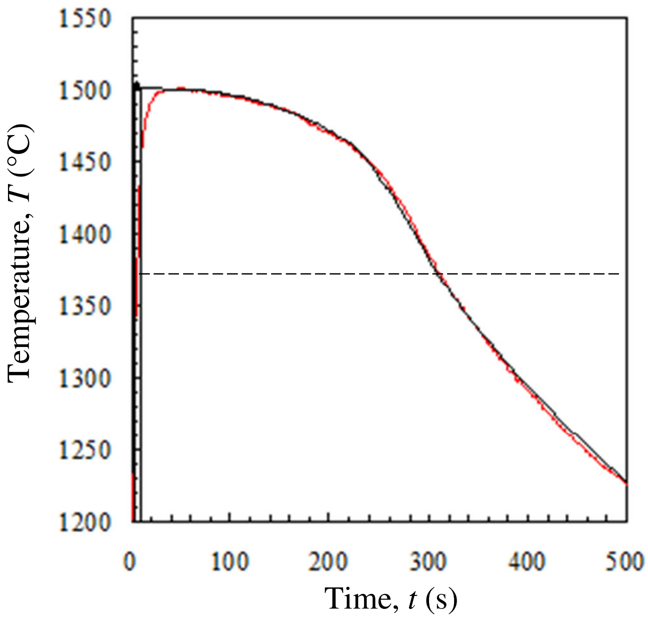


(a)

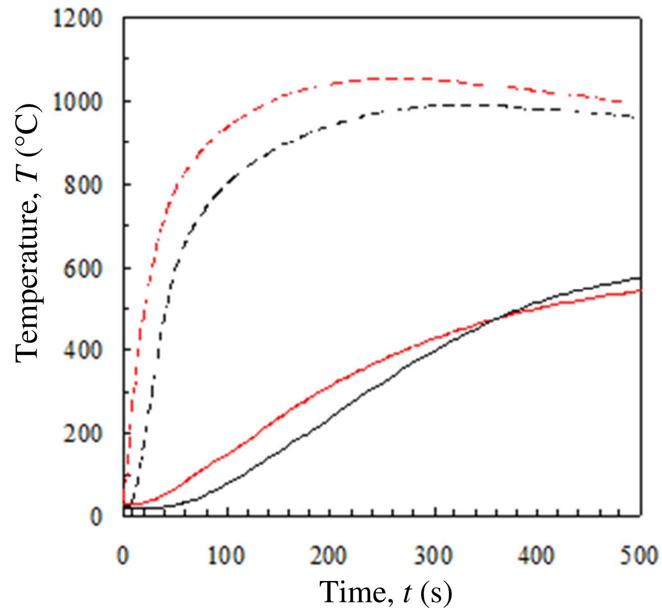


(b)

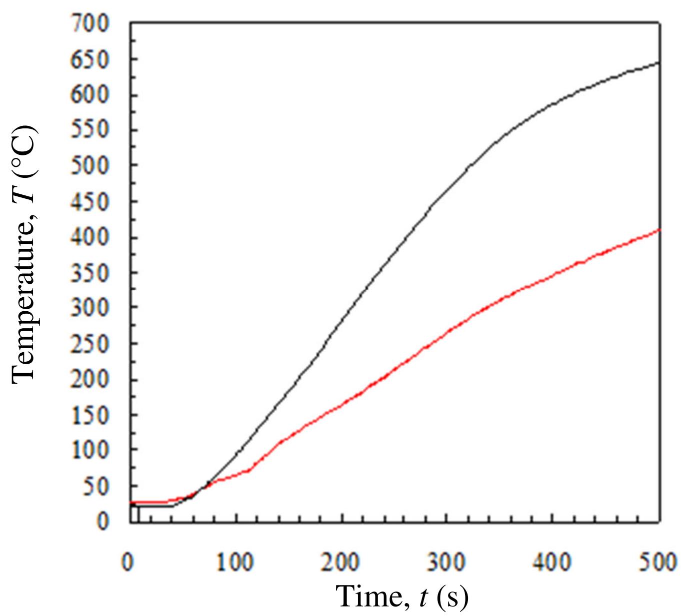
Figure 5. Simulation (black) compared to measured (red) results for the ESPX control casting (a) Steel temperatures. Solidus temperature is indicated by a horizontal black line. (b) Sand temperatures. Lid thermocouple malfunctioned.



(a)



(b)



(c)

Figure 6. Simulation (black) compared to measured (red) results for the ES control casting. (a) Steel temperatures. Solidus temperature is indicated by a horizontal black line. (b) Sand temperatures. (c) Lid temperatures.

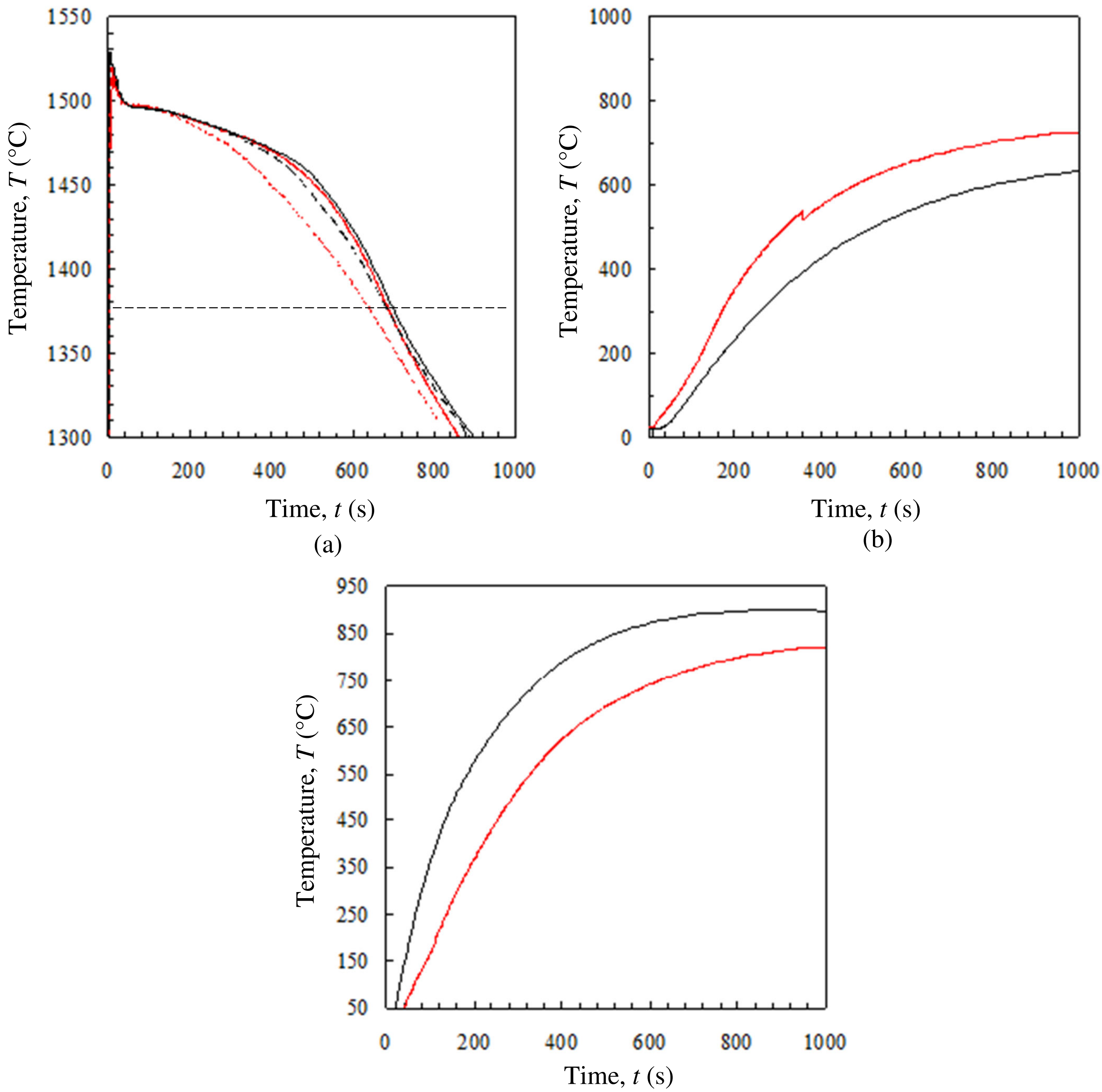


Figure 7. Simulation (black) compared to measured (red) results for the ASK EX control casting. (a) Steel temperatures. Solidus temperature is indicated by a black horizontal line. (b) Sand temperatures. (c) Lid temperatures.

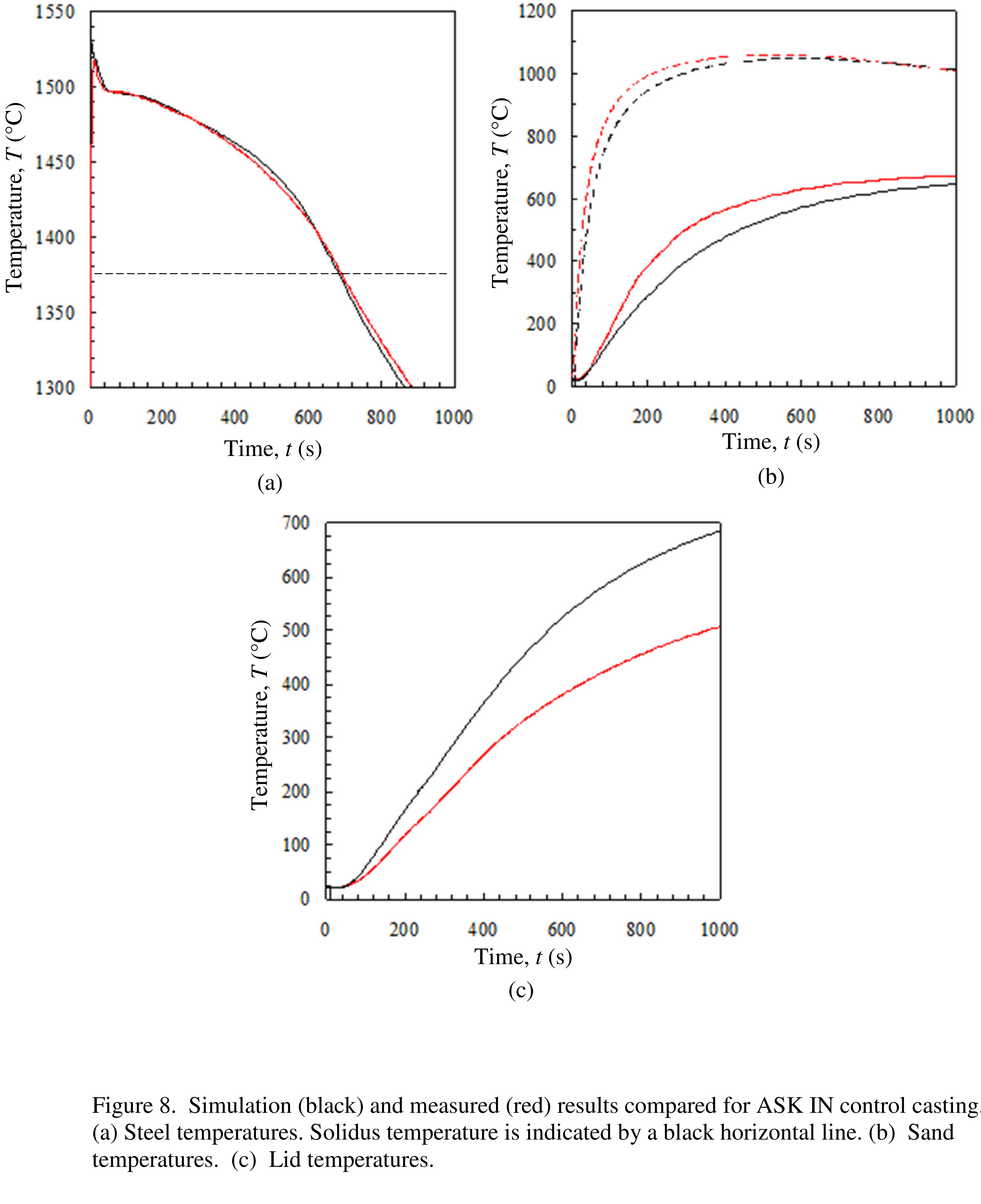


Figure 8. Simulation (black) and measured (red) results compared for ASK IN control casting. (a) Steel temperatures. Solidus temperature is indicated by a black horizontal line. (b) Sand temperatures. (c) Lid temperatures.

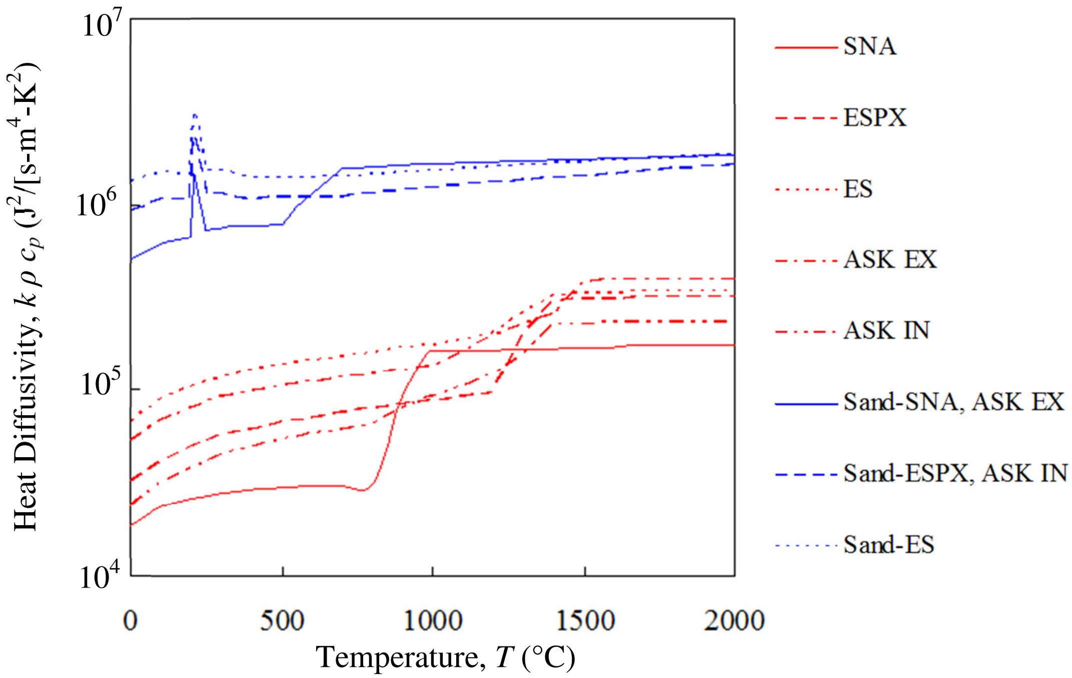


Figure 9. Heat diffusivities for all sleeves shown by red curves. Heat diffusivities for the sand are also included as a reference are shown by the blue curves. Plot is shown on a log scale to illustrate differences in order of magnitude.

geometry or the thickness of the sleeve material. Sleeve thickness is a key geometric parameter which determines a given sleeve's performance. Use of the sleeve properties in simulation along with simulating a given sleeve geometry does allow for a sleeve-to-sleeve comparison. With the completion of this work, this is now possible through simulation. The exothermic properties determined in this work for Exochem ES, Exochem ESPX, and ASK EX sleeves can be found in Table V.

Comparisons between measured (red) and simulated (black) temperatures for the sleeve experiments can be found in Figures 10 to 14. Agreement between the measurements and predictions for the sleeve castings was found to be not as good as that for the control castings at all thermocouple locations. The main criteria used to indicate agreement between the measured and predicted temperatures is achieving good agreement in the steel through the solidification range and the measured time to reach solidus temperature. This is achieved for all the sleeve experiments in Figures 10 to 14. The overall agreement is also good at the sleeve TCs, where the temperatures are very sensitive to error in positioning of the thermocouple. This supports the authors' belief that the developed sleeve properties are accurate for use in simulation. When the predictions are seen to under predict temperatures in the mold sand, it is thought that this difference is due to gas propagation through the mold sand. This results in higher heat transfer and mold temperatures, which indicates that the effective mold thermal conductivity might be changed from that found in the control experiments. The approach used here for sleeve property determination does not allow for the sand thermal conductivity to be changed by the presence of the sleeve. The authors believe modifying the mold sand thermal properties in the presence of

Table V. Exothermic properties for the ES, ESPX, and ASK EX sleeves.

Exothermic Properties			
	Ignition Temperature (°C)	Burn Time (s)	Heat Output (kJ/kg)
ES	830	45	600
ESPX	200	60	520
ASK EX	550	30	425

the sleeve would be an arbitrary approach to achieving temperature agreement in the sand mold. In any event, the effect of sleeve outgassing into the sand does not change the outcome that the effective sleeve properties developed here produce accurate times to solidus and correctly predicts the effective thermal modulus of the sleeved risers. Note also in Figures 10 to 14 that lid temperature predictions in several experiments were seen to be much higher than the measured temperatures. It is believed that this is due to metal flashing between the cope and drag causing a small separation between the lid and the top of the casting. This air gap slowed heat transfer between the two bodies resulting in lower measured lid temperatures than what was simulated.

VI. CONCLUSIONS

Thermophysical properties of five ASK Chemical and Exochem riser sleeves have been developed which accurately predict their performance in casting simulation software. These sleeves included the ES, ESPX, and SNA products from Exochem as well as the EX and IN products from ASK Chemical. The sleeve performance here is determined by the solidification time for sleeved risers and the increase in riser's thermal modulus resulting from the sleeve. The thermophysical properties were presented and validated by showing good agreement between measured and predicted steel temperatures through the solidification temperature range. Previous to this work, such thermophysical data is either unavailable or hidden from software users. Measured temperatures for castings with insulating and exothermic sleeves are compared to a control experiment with no sleeve, and demonstrate the effectiveness of riser sleeves. While the research conducted in this project is still ongoing, the results are encouraging and demonstrate that greater confidence in the solidification modeling of steel castings using sleeves is possible through development of validated sleeve properties. In ongoing work, these sleeve properties are being used to develop new guidelines on sleeve usage. These guidelines will result in the rational usage of sleeves and will be an improvement over the uncertainties inherent in current riser sleeve usage and applications.

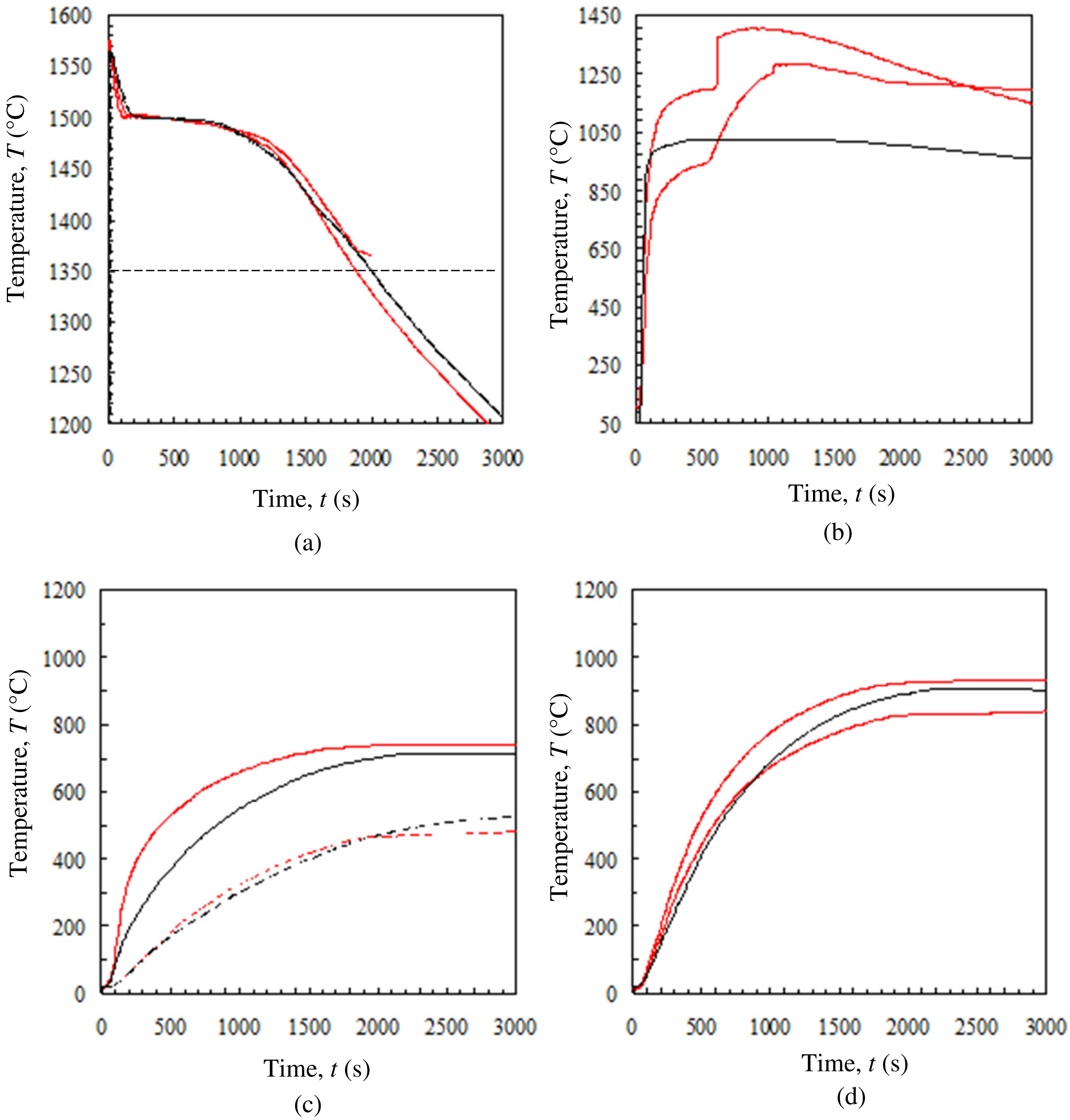


Figure 10. Comparison of simulation (black) and measured (red) results for SNA castings. (a) Steel temperatures. A horizontal black line marks the solidus temperature. (b) Sleeve temperatures. (c) Sand temperatures. Different line types indicate different locations. (d) Lid temperatures.

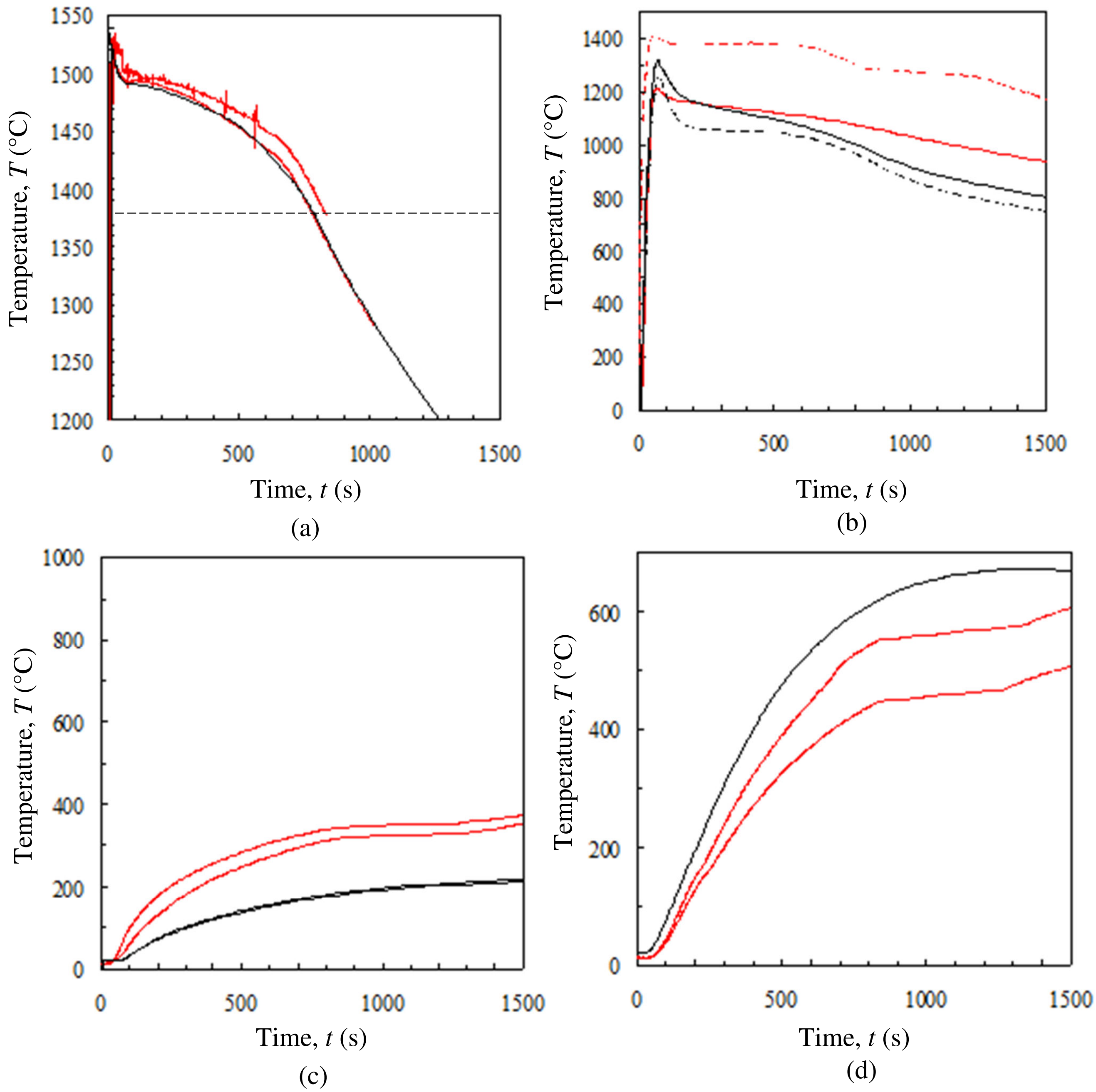


Figure 11. Comparison of simulation (black) and measured (red) results for ESPX castings. (a) Steel temperatures. Solidus temperature is marked with a black horizontal line. (b) Sleeve temperatures. (c) Sand temperatures. (d) Lid temperatures.

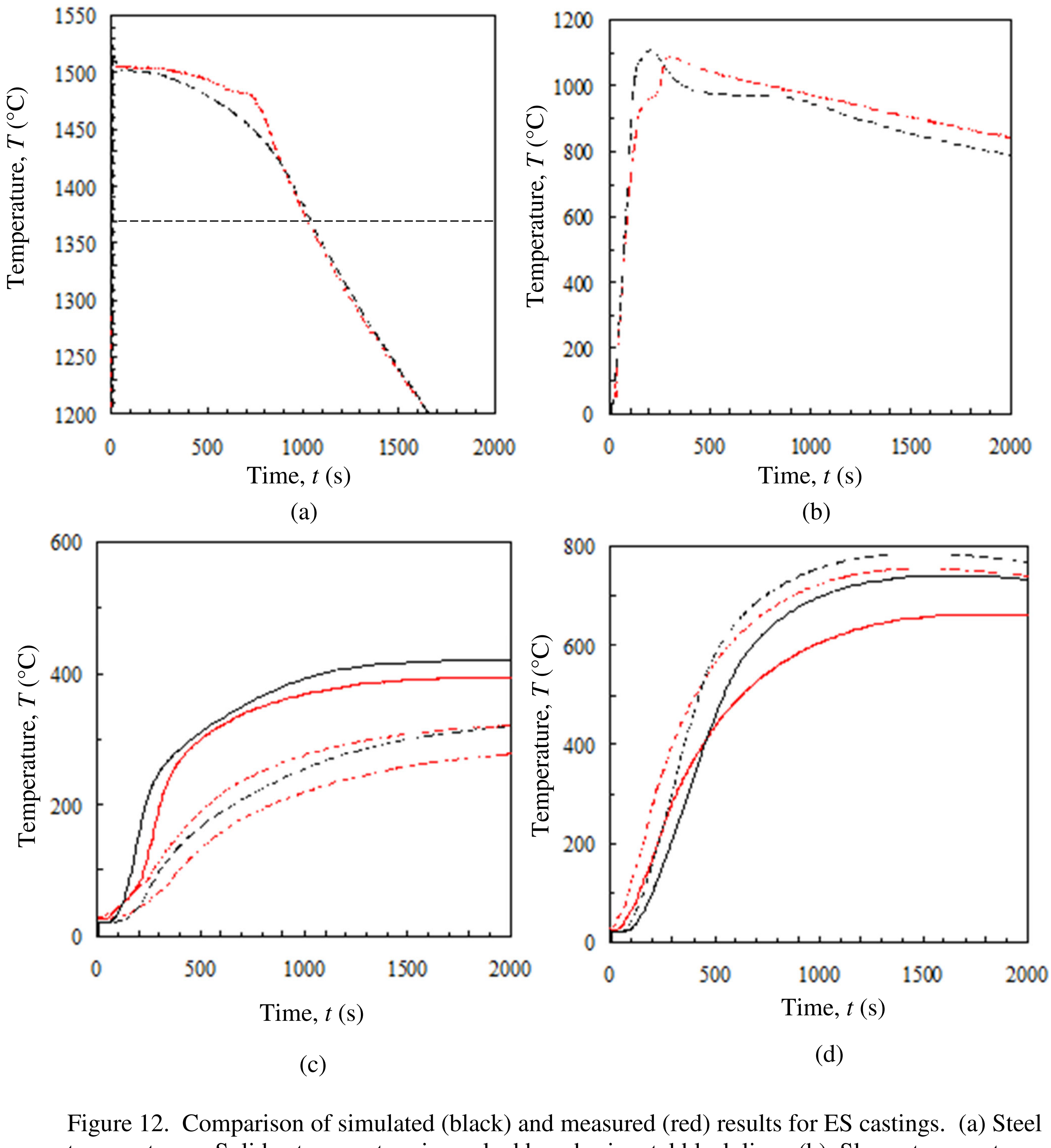


Figure 12. Comparison of simulated (black) and measured (red) results for ES castings. (a) Steel temperatures. Solidus temperature is marked by a horizontal black line. (b) Sleeve temperatures. (c) Sand temperatures. Different line types denote different locations. (d) Lid temperatures. Different line types denote different thermocouple locations.

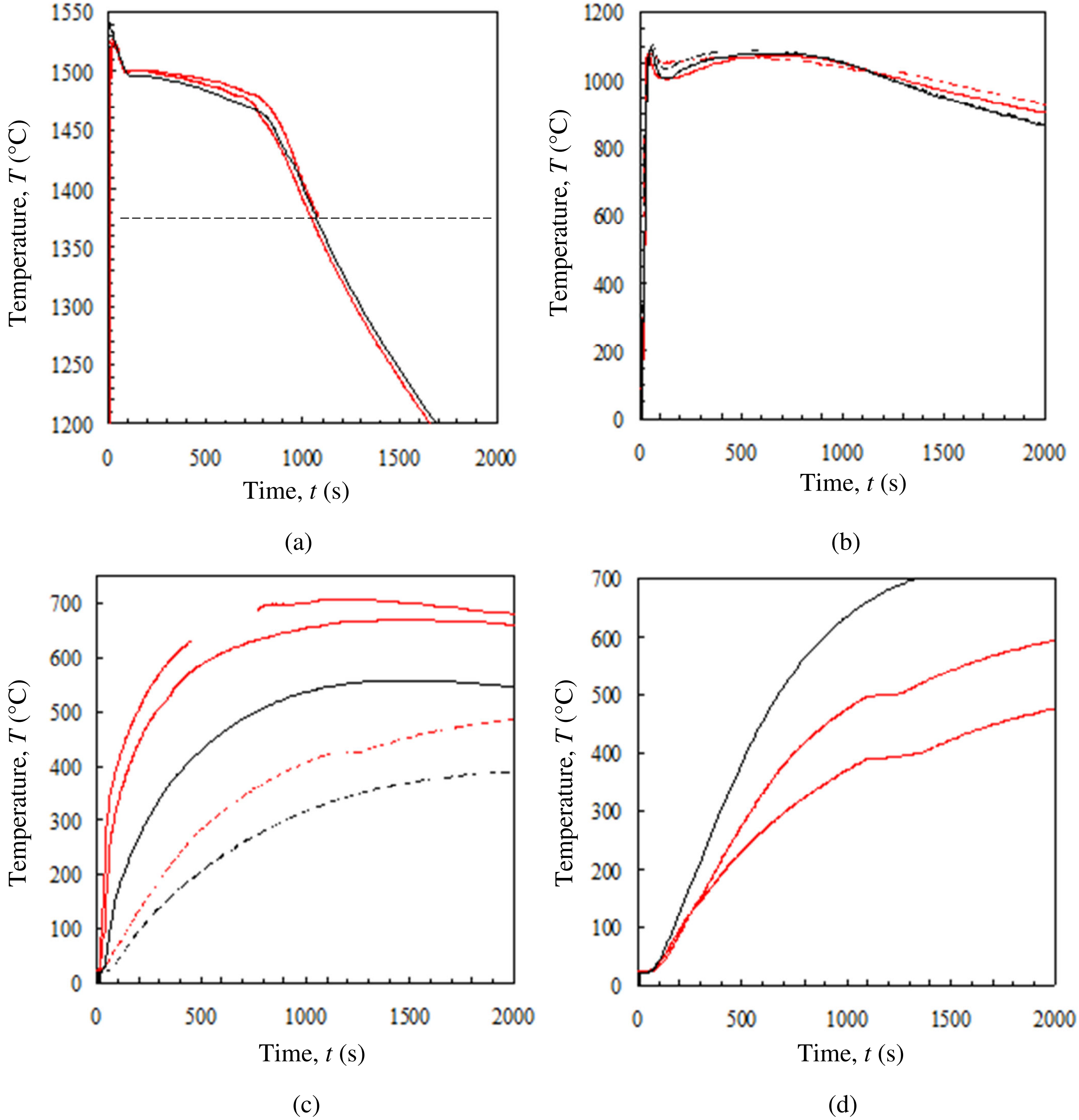


Figure 13. Comparison of simulated (black) and measured (red) results for ASK EX castings. (a) Steel temperatures. Solidus temperature is indicated by a horizontal black line. (b) Sleeve temperatures. (c) Sand temperatures. (d) Lid temperatures.

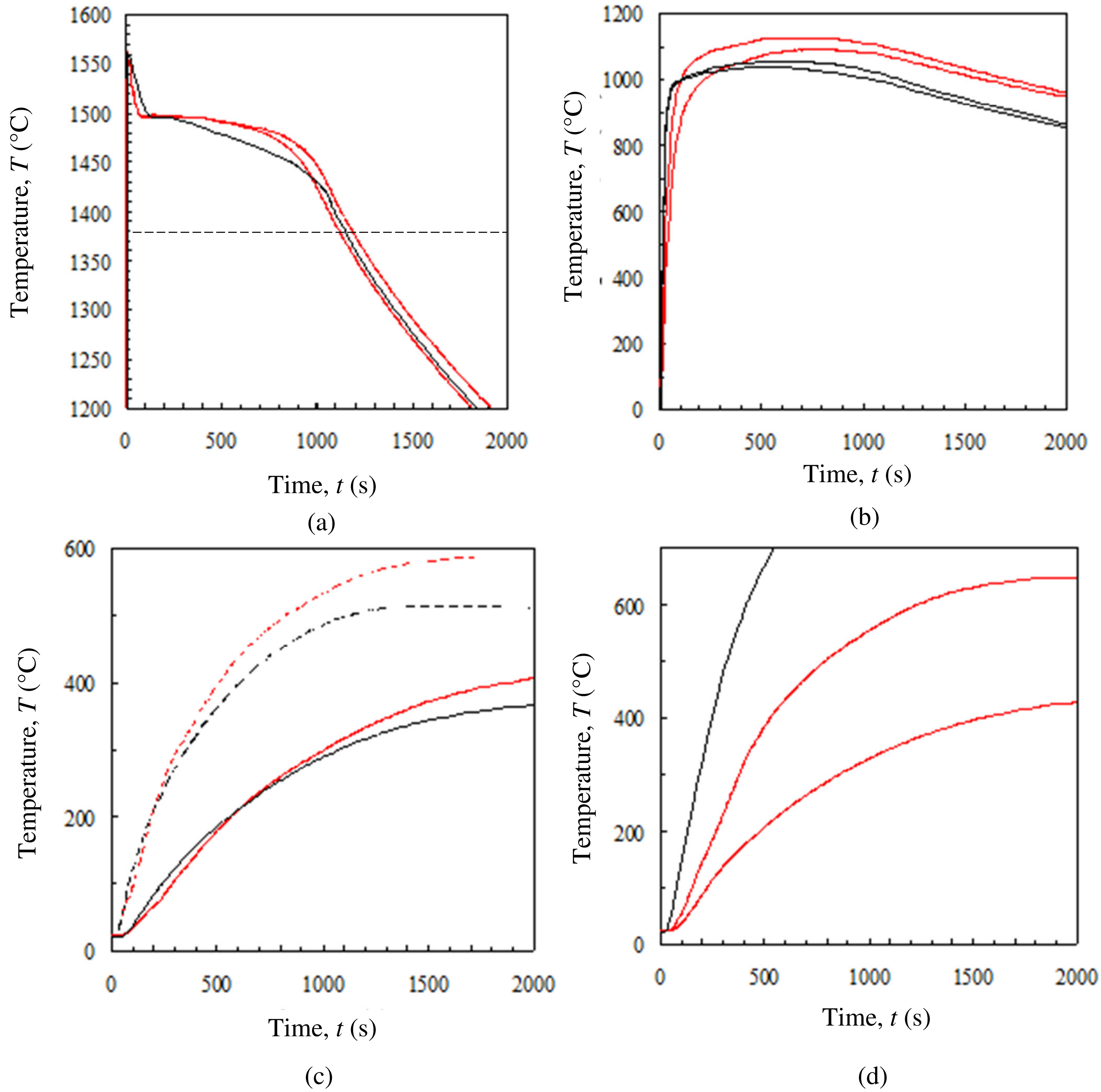


Figure 14. Comparison of simulated (black) and measured (red) results for ASK IN castings. (a) Steel temperatures. Solidus temperature is indicated with a horizontal black line. (b) Sleeve temperatures. (c) Sand temperatures. Different line types indicate different thermocouple positions. (d) Lid temperatures.

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[1] Hardin, R.A., Williams, T.J., and Beckermann, C., "Riser Sleeve Properties for Steel Castings and the Effect of Sleeve Type on Casting Yield," in Proceedings of the 67th SFSA Technical and Operating Conference, Paper No. 5.2, Steel Founders' Society of America, Chicago, IL, 2013.

Appendix A: Thermophysical Properties used in Control Experiments

The properties determined for the control casting experiments used in the simulations follow below. In Figure A1 the steel thermal conductivity, density and specific heat curves are given. Based on the liquidus and temperatures of a steel cast in a given experiment, the curves

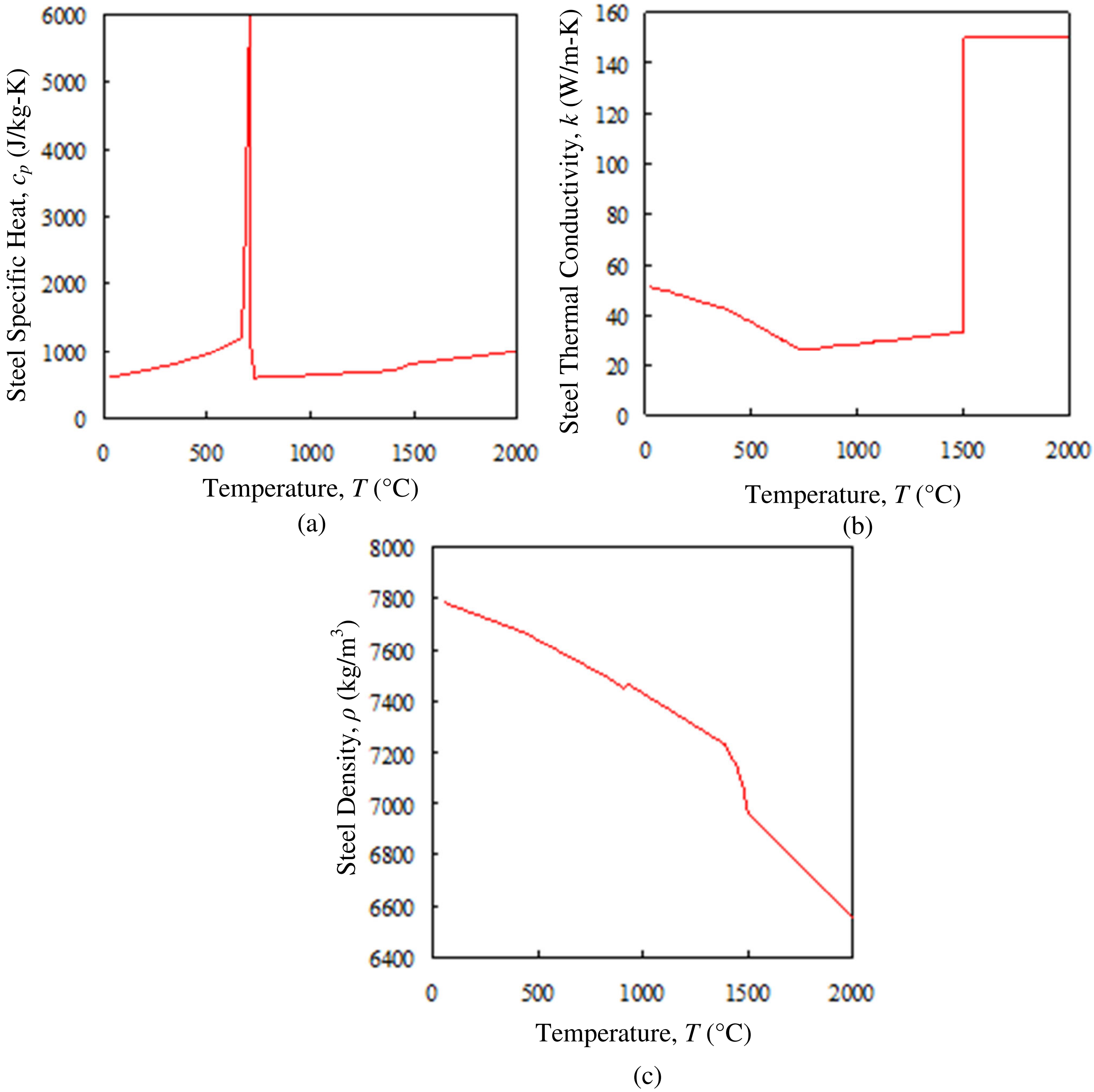
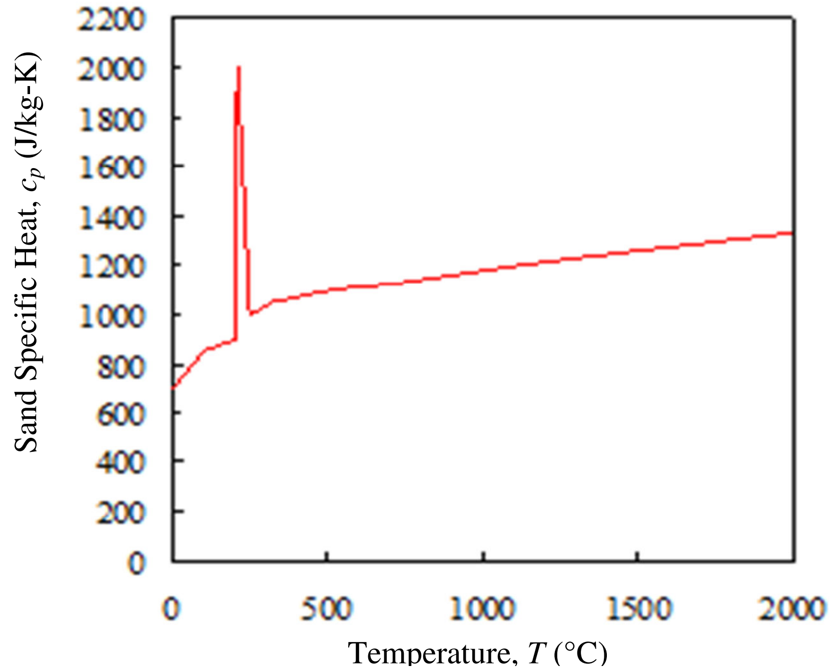
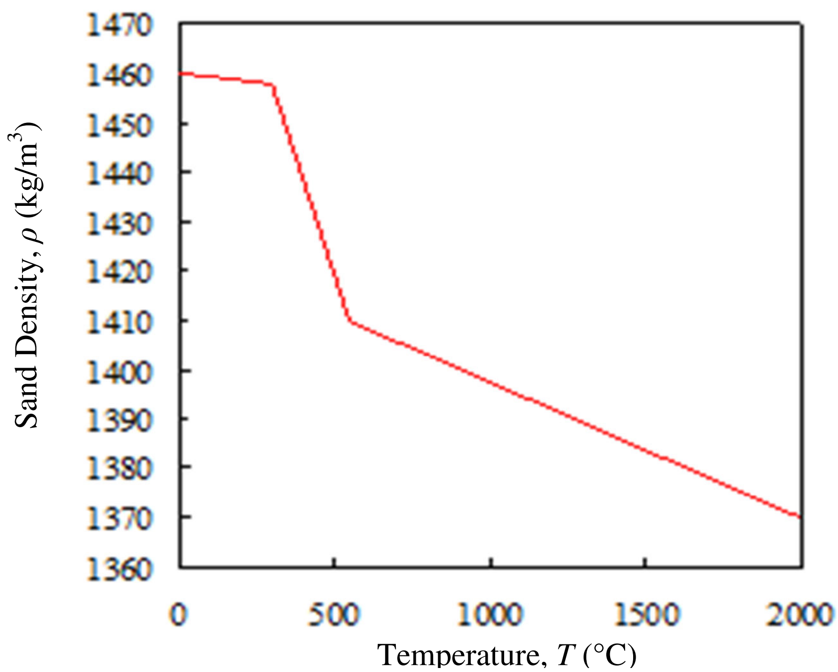


Figure A1. General steel properties. (a) The specific heat used for all simulations. (b) An example of the thermal conductivity. (c) An example of the density curve.

were adjusted for a given experiment. At the liquidus temperature of a given steel poured, there is an increase in the steel thermal conductivity from 33 to 155 W/m-K to account for convective heat transport. A "jump" in density of the steel seen in Figure A1c begins at the liquidus temperature and ends at the solidus temperature.



(a)



(b)

Figure A2. General sand properties. (a) The sand density curve used for all simulations. (b) The sand specific heat curve used for all simulations.

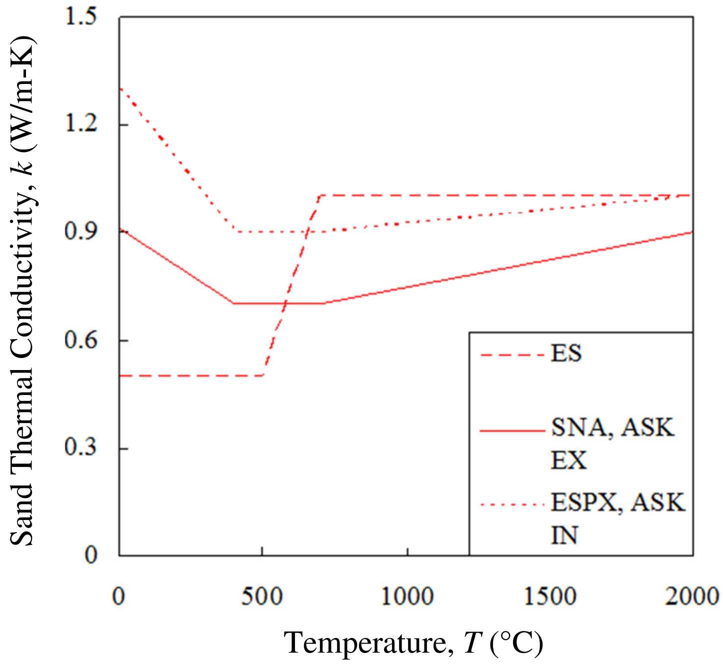


Figure A3. Sand thermal conductivity curves used in simulations. Curves are labeled according to which control simulation they were used in.

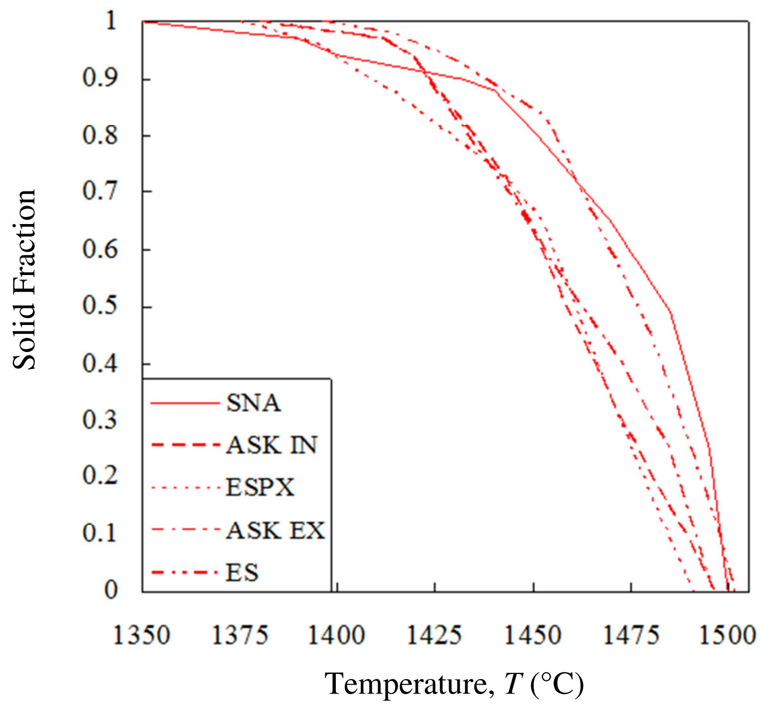


Figure A4. Solid fraction curves used in simulations. Curves are labeled according to which control and sleeve simulations they were used in.