Modeling Blast Furnace Hearths

by

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Introduction

The penetration of molten iron into the carbon hearth of a blast furnace can lead to erosion of the hearth material and eventual failure of the hearth. The prediction of temperature distributions in hearths and of the resultant iron penetration is a concern from the standpoint of both safety and economy. Many approaches to the mathematical modeling of blast furnace hearths have appeared.[1-4] This report describes the application of a finite element model of steady-state heat transfer to the study of blast furnace hearths.

Finite Element Model

The furnace hearth is assumed to be represented by a thick bottomed, axisymmetric "cup" containing a mixture of coke and molten metal. The high thermal conductivity of the molten metal, coupled with the circulation of the metal bath, is assumed to maintain a constant temperature boundary condition on the inner surface of the original hearth. This condition has been indicated, with a boundary temperature of approximately 2700°F, in studies of the circulation of the molten metal bath.[5] The external surfaces of the hearth are assumed to be convection cooled with the convection coefficient and the coolant temperature determining the differences among stave cooling, underhearth air cooling, and contact with deep soil. Molten metal is assumed to penetrate any portion of the carbon hearth which reaches a temperature in excess of the eutectic temperature of the iron-caron system, approximately 2100°F. The carbon with metal in the pores is assumed to have a thermal conductivity between that of carbon and of pure iron. This conductivity is frequently assumed to be approximately 9 BTU/ft-hr-°F, but can be adjusted to fit individual furnaces. During the life of the hearth, the carbon is eroded/dissolved to form a "sludge" called salamander. This process of converting carbon to salamander is assumed to be slow compared to the rate of attaining essentially steady-state temperatures. In this steady state model, the transition from pure carbon to metal containing carbon is assumed to occur abruptly at the eutectic temperature and is modeled as an abrupt change in thermal conductivity. The model reported here does not treat the paste layers, the steel shell, or the anisotropy of the carbon hearth materials. The geometry and composition of the hearth is otherwise essentially arbitrary and furnaces with as many as five different components in the hearth have been studied.

Results

The radial temperature distribution at the bottom of the carbon hearth has been reported[6] for a blast furnace with a stave diameter of approximately 30 feet. This furnace had a carbon hearth eight feet thick sitting on a ceramic subhearth seven feet and one inch thick. The temperature distribution along the bottom of the carbon was calculated with the model and compared to the thermocouple readings reported in Reference 6. The calculations assumed that contact of the hearth with the soil could be modeled as convective cooling to a coolant temperature of 100°F. The comparison between calculated and experimental temperatures is shown in Figure 1. The calculated temperatures are within approximately 100°F of the experimental results at all radii. Reference 6 also reported a steady state temperature of 720°F at the bottom of the ceramic subhearth. The model calculations gave 650°F at this point. This result and those in Figure 1 demonstrate the ability of the finite element model to give an acceptable account of the temperatures in blast furnace hearths.

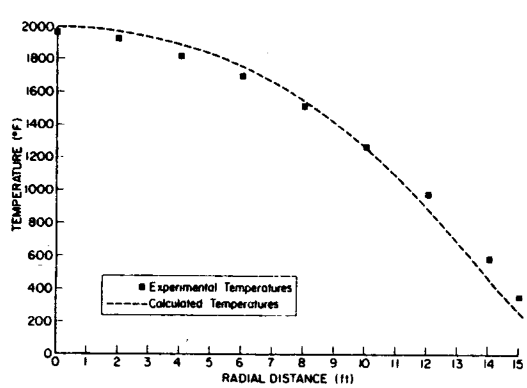

Figure 1. Comparison of Predicted and Measured Temperatures Across the Bottom of a Thirty Foot Blast Furnace Hearth.

The model was used for a parametric study of the response of blast furnace hearths. The maximum temperature along the bottom of the carbon hearth and the depth of penetration of molten metal into the carbon were taken as the responses of most interest. The parameters which were varied included furnace type and diameter, L/D ratio, and the temperature assumed for the top boundary condition. The furnace types considered were: the "PL" furnace consisting of carbon on a ceramic base, the "PLG" type in which the lower 20% of the carbon of a PL furnace is replaced by a graphite cooling layer, the "PLGC" type in which the lower 20% and the upper 20% of the carbon are replaced by a graphite cooling layer and by a ceramic plug respectively, and the "UHC" type in which the carbon hearth rests on a forced air cooling system. The furnace diameter is taken to be the ID of the staves. The L/D ratio is the ratio of the total thickness of the carbon and any replacements, such as graphite or ceramic plug, to the diameter of the furnace. A value L/D = 0.25 is often used as a target in hearth design. The top boundary condition has been indicated[5] to be approximately 2700°F, but may depend on furnace operation. The average responses to each of the parameters is indicated in Table I. The penetration of the molten metal is expresed as a percentage of the hearth depth L and the temperature at the bottom of the hearth is in °F. Each entry in the table represents the average of eight computer runs with very different sets of parameters. For this reason, the results cannot be used to predict the behavior of any particular furnace, but only to indicate trends which require more extensive investigation.

Table 1. Summary of the Effect of Furnace Design and Operation on Performance. Each Effect is the Average of Eight Cases.

Parameter	Value	Average Effects: Penetration (%)	Average Effects: Bottom Temperature (°F)
Type	PL	96	2132
	PLG	64	1621
	PLGC	59	1615
	UHC	44	688
Diameter (Feet)	24	71	1595
	32	65	1498
	40	66	1474
	48	59	1490
L/D	.19	92	1843
	.23	66	1518
	.27	60	1465
	.31	45	1230
Top Boundary Temperature (°F)	2500	54	1371
	2600	60	1440
	2700	70	1602
	2800	78	1640

Discussion

The results in Table 1 show the dramatic reductions in metal penetration and bottom temperature when cooling is added to the bottom of the hearth. The PL furnaces, without bottom cooling, have molten metal penetration essentially through the whole thickness of the carbon hearth. When the lower 20% of the thickness of the carbon is replaced by a graphite cooling layer, the PLG and PLGC furnaces, the penetration is reduced to approximately 60% of the total thickness of carbon plus graphite. The inclusion of a ceramic plug has little effect on the responses studied here. Air underhearth cooling, UHC, further reduces the penetration and temperatures.

The diameter of the furnace was found to have little effect on penetration and bottom temperatures. This finding is at variance with the reported behavior of operating blast furnaces. This discrepancy is a result, at least in part, of expressing penetration as a percentage of the hearth thickness L. Since furnace design practice tends to increase L with increased diameter to maintain approximately constant L/D, the actual penetration in inches would be expected to increase with increasing D even when the percentage penetration was constant. The actual value of the ratio L/D can be seen from the table to have a strong effect on both the penetration and the bottom temperature. There is a suggestion of a plateau in the response of the furnace to L/D in the region of the usual design target of L/D = 0.25.

The previous parameters, furnace type and diameter and L/D, dealt with the influence of furnace design on hearth performance. The effect of the top boundary temperature on penetration and bottom temperature shows the influence of furnace operation. This temperature was indicated[5] to be approximately 110°F less than the tapping temperature. As one would expect, hotter operation of the furnace has the direct result of deeper penetration and, eventually, deeper erosion and higher temperatures to which the cooling system or ceramic base are subjected.

References

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