

Introduction of a novel, scrap-based, fully continuous steelmaking process

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ABSTRACT

An attempt to significantly improve meltshop efficiency has led to the development of a new process to melt, refine, alloy, and cast steel, using a system of interconnected vessels. In the proposed process, the steel will be continuously melted in a 55-t Consteel EAF and flow through three refining vessels and a tundish before entering the mold. The reactors and their functions are described and illustrated. The expected chemistry changes, alloying effects, energy requirements, and general operating procedures of the process based on process simulation are presented. Predictions are made about size of the meltshop building, required processing times, possible production rates, and effects of changing operational conditions. Several corrective actions for upset conditions and maintenance issues are described, including the procedures for grade changes.

INTRODUCTION

Steelmakers always search for ways to decrease the cost of steelmaking while increasing productivity, production rates, and the steel quality. The design of a novel, scrap-based, fully continuous steelmaking process is an effort to provide steelmakers with a technology that would allow them to achieve these goals beyond the possibilities of current technologies. The new steelmaking process was designed to give steelmakers a reliable and flexible tool that is able to vary the production rate as required by market demands, maintenance, and unscheduled delays.

This document is an introduction of the continuous steelmaking process. More details and research results about this process will be discussed in subsequent publications. General benefits of this new process were summarized in a previous publication¹. The fluid flow within the refining vessels of the process is described in a concurrent publication by Zhang et al².

OVERVIEW OF PROCESS

The proposed continuous steelmaking process, as shown in Figure 1, is designed to replace a steelmaking shop that currently uses an Electric Arc Furnace (EAF), a Ladle Metallurgy Furnace (LMF), and a Continuous Caster (CC). The process is designed to allow for variation of the production rate as required between 70 t/hr and 170 t/hr, making the process flexible to changing demands. It is estimated that the process could operate for one week or longer without interrupting the steel production with an expected weekly maintenance downshift of 8-12 hours.

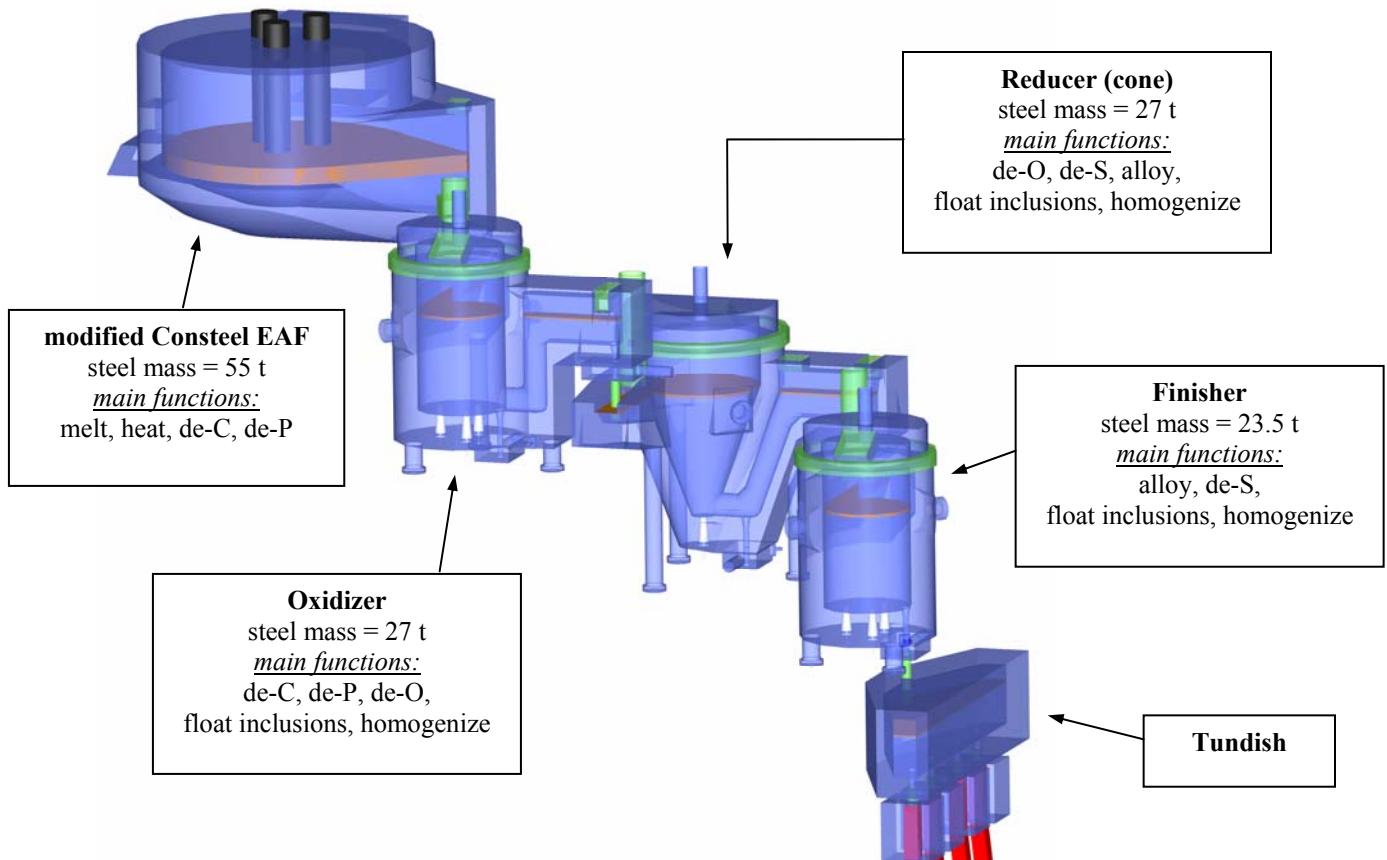


Figure 1: Transparent side view of the fully continuous steelmaking process (right side)

Steel will continuously flow through five interconnected vessels during the operation of the continuous steelmaking process. Preheated scrap will be continuously charged and melted in the first vessel (modified AC Consteel EAF). Melting will be accomplished with electrical and chemical energy while maintaining a foamy slag and performing preliminary de-C and de-P. Final de-C and de-P will be achieved in the second vessel (Oxidizer). Near-equilibrium conditions allow for a partial de-O of the steel in the Oxidizer, depending on the required final carbon concentration. In the third vessel (Reducer), steel will be continuously de-O, de-S, and alloyed. The cone-shaped Reducer is designed to increase the kinetics and decrease the final sulfur concentration while maintaining a high production rate. Steel that has a composition that is close to the final chemistry will enter the fourth vessel (Finisher). The operations in the Finisher will include final trimming, additional de-S, inclusion floatation, and homogenization before the steel will flow into the fifth vessel (Tundish).

The vessels are designed for fast, near-equilibrium reactions to ensure a large degree of control, productivity, flexibility, and to reduce maintenance with oxidizing conditions in the first two vessels (EAF, Oxidizer) and reducing conditions in the Reducer and Finisher. A series of two vessels with similar near-equilibrium conditions allows for optimum refining and for the minimization of variations in fluid flow (residence time distributions) and composition (chemistry, inclusion), contributing to the reliability and flexibility of the process. The sequential refining and the near-equilibrium, steady-state operation of the continuous process allow for increased refining and reduced alloy and flux consumptions as compared to the current EAF-LMF steelmaking route.

The continuous steelmaking meltshop, as sketched in Figure 2, is projected to require less than one third of the footprint of a conventional meltshop, decreasing capital and operational costs, man-hours per ton of cast steel, and processing times. A typical scrap-based meltshop that uses a Consteel EAF is sketched next to the projected continuous steelmaking meltshop in Figure 2, illustrating the size difference between these two types of meltshops. The continuous steelmaking meltshop will be smaller than current meltshops because the transport and maintenance of ladles will be eliminated and because the size and amount of equipment will be reduced.

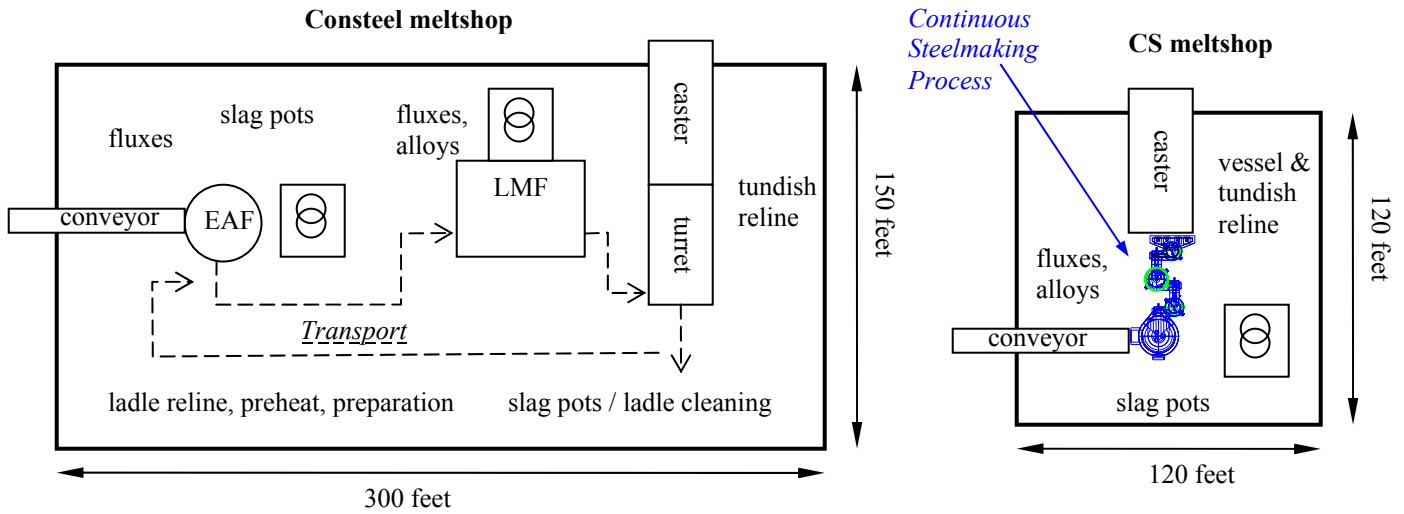


Figure 2: Schematics of a representative Consteel meltshop and the projected Continuous Steelmaking (CS) meltshop

The capacity of the EAF (55 tons) will be less than one-half of the size of a typical EAF that produces steel at a rate of 170 t/hr. The LMF and all the auxiliary equipment would be replaced by three small refining vessels, reducing the number of alloy and flux hoppers and eliminating one transformer and the associated energy. The elimination of ladles, including their transport and maintenance, results in the reduction of size and number of over-head cranes and their energy usage as well as the elimination of the space and energy for cleaning, storing, transporting, relining, and reheating ladles. These changes not only reduce costs and auxiliary energy consumption but also increase safety because less heavy equipment will be moved during steel production and overhead transport of hot, liquid steel will be eliminated.

The continuous steelmaking process is compact, using approximately the same amount of space as a typical turret system at a continuous caster. The size of the continuous steelmaking design as compared to two 150-ton ladles, sitting in the casting and holding position of a turret, is illustrated in Figure 3a and 3b. Figure 3a shows that the new design would occupy approximately one thousand square feet in front of the caster. It is shown in Figure 3b that the top of the EAF would be approximately 30 feet above the tundish or 15 feet above the top of a ladle, sitting in the casting position.

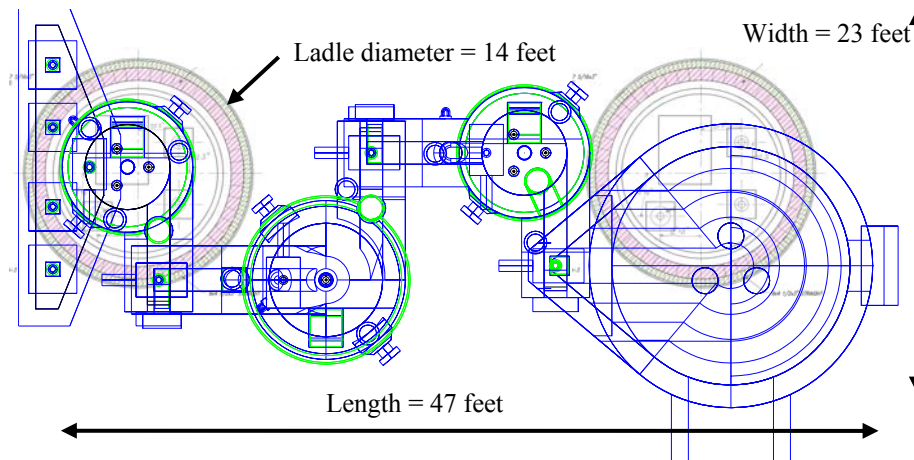


Figure 3a: Top view of the continuous steelmaking design superimposed on drawing of two ladles, sitting on a typical turret

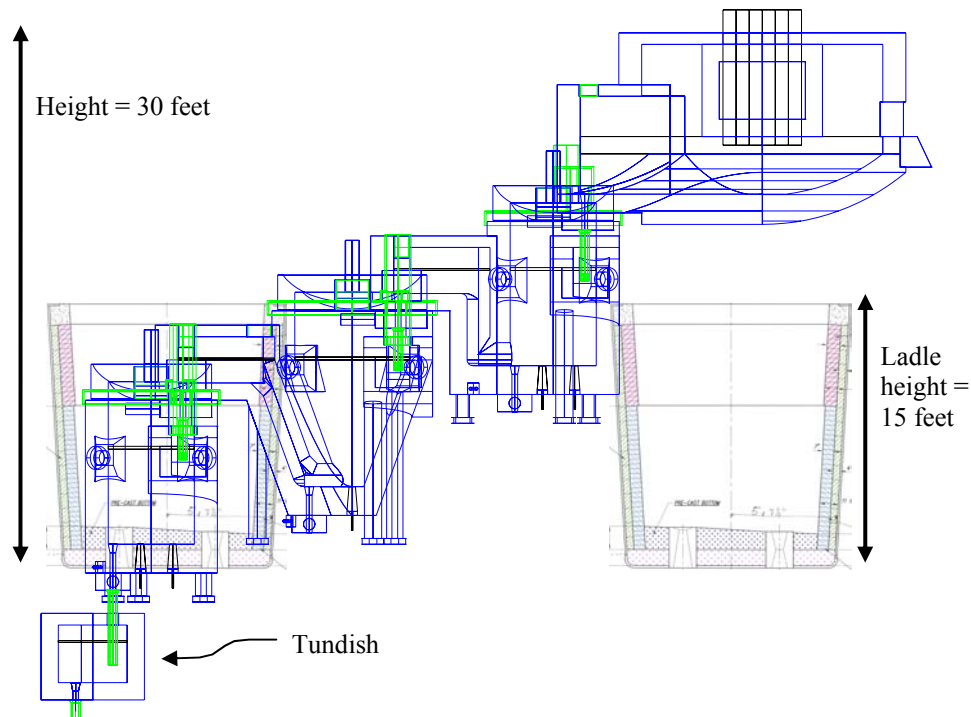


Figure 3b: Left-side view of the continuous steelmaking design superimposed on drawing of two ladles, sitting on a typical turret

DESCRIPTION AND ILLUSTRATIONS OF VESSELS 1 THROUGH 4

Modified Consteel EAF (vessel 1)

Preheated scrap and fluxes will be charged continuously into a modified AC Consteel EAF as illustrated in Figure 4. Preheating the scrap reduces the size of the vessel by minimizing the amount of required electrical energy. By charging and tapping continuously, the furnace will run with 100% power-on and a constant 55-ton liquid heel (full furnace). An AC power supply was chosen to avoid the maintenance of a bottom electrode, increasing the duration of continuous campaigns.

The inner diameter of the furnace is 13.8 feet and the fill height is 2.3 feet. The tap hole is 4 inches in diameter, similar to the tap holes in vessels 2 through 4. The EBT bottom is lowered so that it is level with the lowest point of the furnace. This modification together with the constant high fill height eliminates the carry-over slag during steady-state operation and it allows for the complete draining of the EAF into the Oxidizer without tilting the furnace. The flow from the EAF into the inlet launder of the Oxidizer will be regulated by a slide gate.

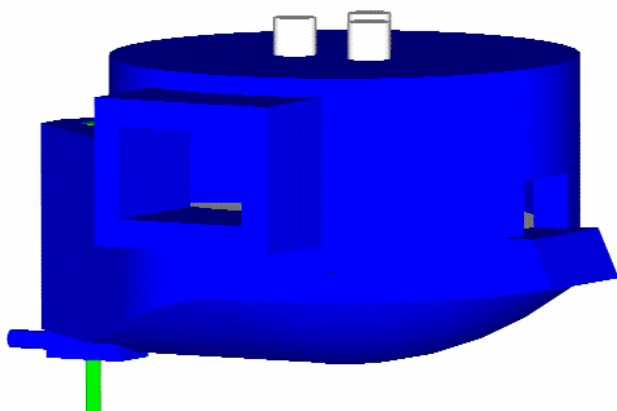


Figure 4a: Left-side view of modified Consteel EAF (vessel 1)

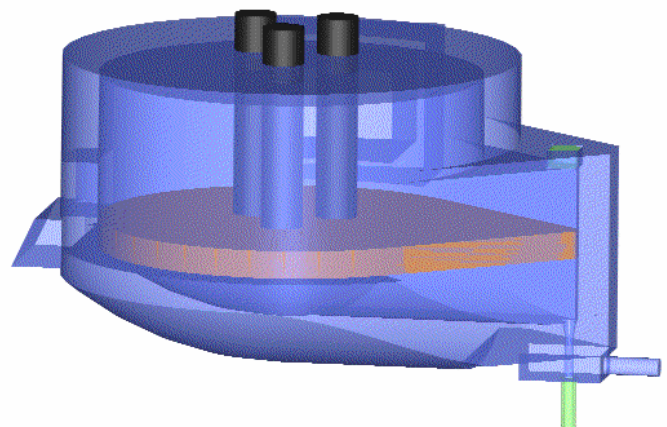


Figure 4b: Transparent right-side view of vessel 1

Oxidizer (vessel 2)

Additional de-C and de-P will be accomplished in the 27-ton Oxidizer shown in Figure 5, allowing for high carbon content and iron yield in the EAF and low final carbon and phosphorus concentration. The steel enters the cylindrical vessels through a 1.3-ft wide by 4.0-ft long inlet launder that is located off-center to the main vessel, producing a swirl in the steel bath and minimizing the chance of short circuiting. The Oxidizer has an inside diameter of 4.9 ft and is designed to operate at a bath depth of 5.4 ft, providing 3.7 ft in freeboard above the bath. The bath will be stirred by injecting argon through three bottom porous plugs, ensuring constant and homogeneous stirring even if one porous plug fails. Three porous plugs produce small bubbles, increasing the gas/steel interface to promote degassing reactions and the floatation of inclusions. The fluid flow in the Oxidizer is described in detail by Zhang et al².

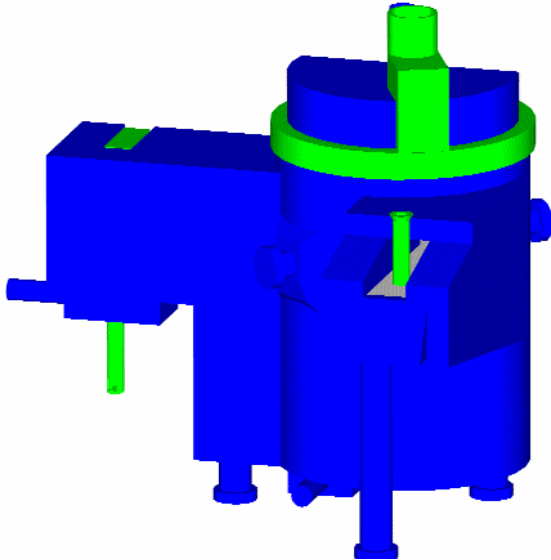


Figure 5a: left-side view of Oxidizer (vessel 2)

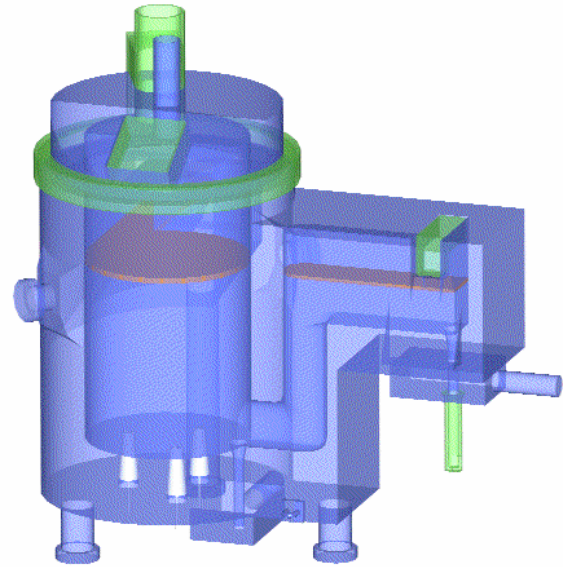


Figure 5b: transparent right-side view of vessel 2

The metal exits the Oxidizer through a 1.3-ft wide by 5.5-ft exit channel, which is designed to remove steel from the vessel near the bottom to reduce short circuiting and slag carryover without requiring the height that would be needed with a bottom tap design. If required, the steel can be removed through a bottom tap hole or by pouring the steel through the inlet channel after the vessel is removed from its location and tilted by a crane. A door in the outlet channel allows for periodic renewing of the slag cover in this channel and for access to the tap hole that is equipped with a slide gate.

Spent slag will be continuously removed through the inlet launder. The inward stream of steel within the inlet launder creates an outward flow on the upper surface, continuously transporting the slag to an overflow and eventually into the slag pot placed below the inlet launder. Off-gases will be evacuated through a duct in the removable roof that rests on the main vessel. A door located in the angled part of the roof provides access and a mean of observation during operation. Fluxes (and alloys if required) are periodically added through the center of the roof.

The wall of the vessel is 16 inches thick, allowing for the placement of 9-inch refractories and 5-inch insulating bricks as well as the structural support of a steel shell. Magnesia-graphite refractory will be used for the slag line and the rest of the vessel will be lined with resin-bounded magnesia. These materials resist penetration because they have little porosity. Refractory losses associated with thermal cycling, erosion, and corrosion will be reduced as compared to ladle treatment because consistent temperature and chemical conditions exist in each refining vessel and because frequent forceful tapping streams and the cleaning of ladles with oxygen will be eliminated.

Reducer (vessel 3)

The steel is deoxidized, desulfurized, and alloyed in the 27-ton Reducer illustrated in Figure 6. The steel enters the vessel in an inlet launder similar to the inlet launder used in the Oxidizer, which is designed to enhance homogenization of the bath. The conical-shaped vessel is designed with an upper inner diameter of 6.6 ft, a lower inner diameter of 1.3 ft, and an operating depth of 7.2 ft of steel, providing 3.7 ft of freeboard similar to the Oxidizer. Steel will be stirred with argon through one porous plug located in the bottom of the vessel. The top area of the steel bath is 34 ft², nearly twice the top area of the Oxidizer, which has similar tonnage capacity. The conical shape increases the fraction of the steel that is highly stirred and the slag/metal interface. These improvements maximize the energy input to the steel bath, the reaction rates, the sulfur removal, the homogenization of temperature and chemistry, as well as possible production rates.

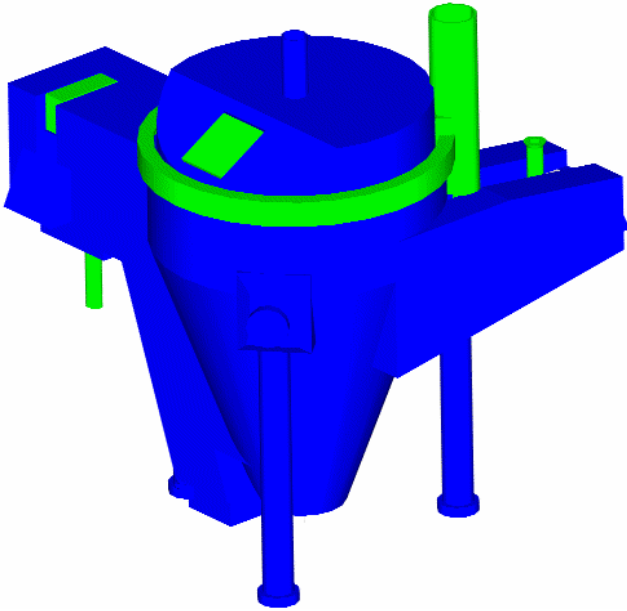


Figure 6a: left-side view of Reducer (vessel 3)

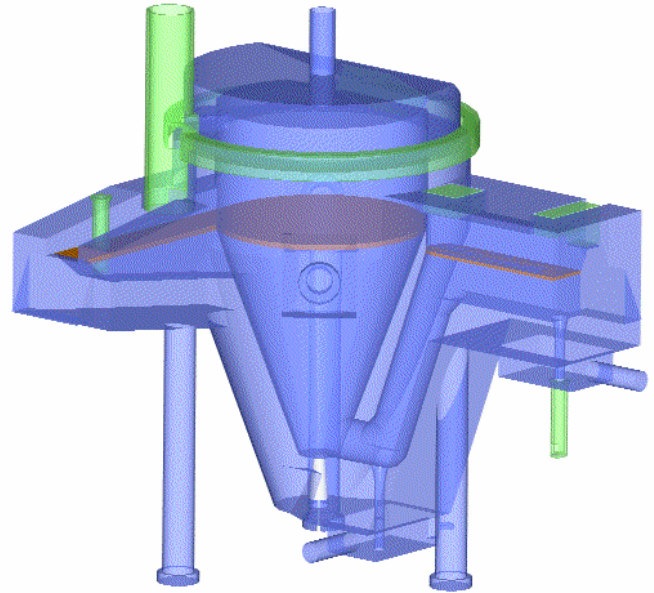


Figure 6b: transparent right-side view of vessel 3

In addition, the conical shape allows for concentration differences between subsequent grades because lowering the fill height during grade change to the level of the outlet tap hole results in the removal of half of the steel from the Reducer. The exit channels of the Oxidizer and Reducer are similar except that the emergency bottom tap hole of the Reducer is moved. Other similarities between the two vessels are the continuous deslagging through the inlet launder, the location of the alloy and flux chute, the wall design, and the ability to empty the vessel by tilting. The off-gas system is designed to provide improved control of the atmosphere within the Reducer by minimizing air infiltration.

Finisher (vessel 4)

Final alloying or trimming as well as additional de-S is performed in the 23.5-ton Finisher illustrated in Figure 7. The Finisher is similar to the Oxidizer except that the off-gas system is designed to minimize air entrapment and the steel is tapped through the bottom tap hole. Bottom-tapping allows for complete emptying of the Finisher during grade changes similar to ladles in current casting operations. However, during normal operations, the steel level remains constant with continuous argon bubbling at low flow rates, maximizing chemistry and temperature homogeneity and the cleanliness of the steel. Auxiliary heating of the steel during refining is not required during normal operation of the continuous steelmaking process. If unexpected delays require additional heating, it could be done with a non-contact twin plasma torch³ in the Finisher by inserting the heater through the roof door.

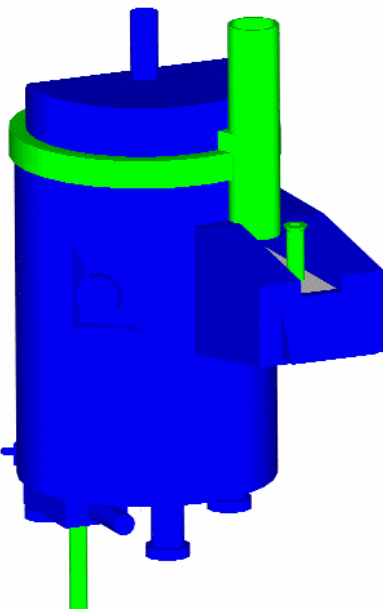


Figure 7a: left-side view of Finisher (vessel 4)

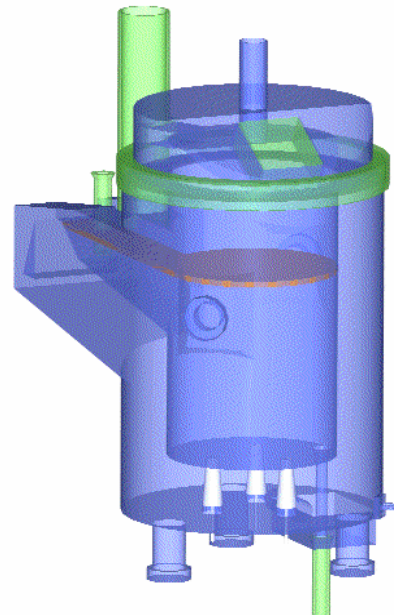


Figure 7b: transparent right-side view of vessel 4

OPERATING PROCEDURES

Steady state operation of the continuous steelmaking process

The new process would make it possible to convert solid scrap to finished continuous cast product in less than two hours at a production rate of 110 t/hr. The average residence time is 30 minutes in the EAF and approximately 15 minutes in each of the three refining vessels and the tundish.

The vessels of the continuous steelmaking process are shown with the placement of slag pots and partly-drawn working platforms in Figure 8. Each of the three slag pots are placed to allow for collection of the slag from one entry launder and from the exit door of the previous vessel in the same slag pot. The working platforms are designed to provide access to all doors and the entry launders so that each vessel can be maintained and operated.

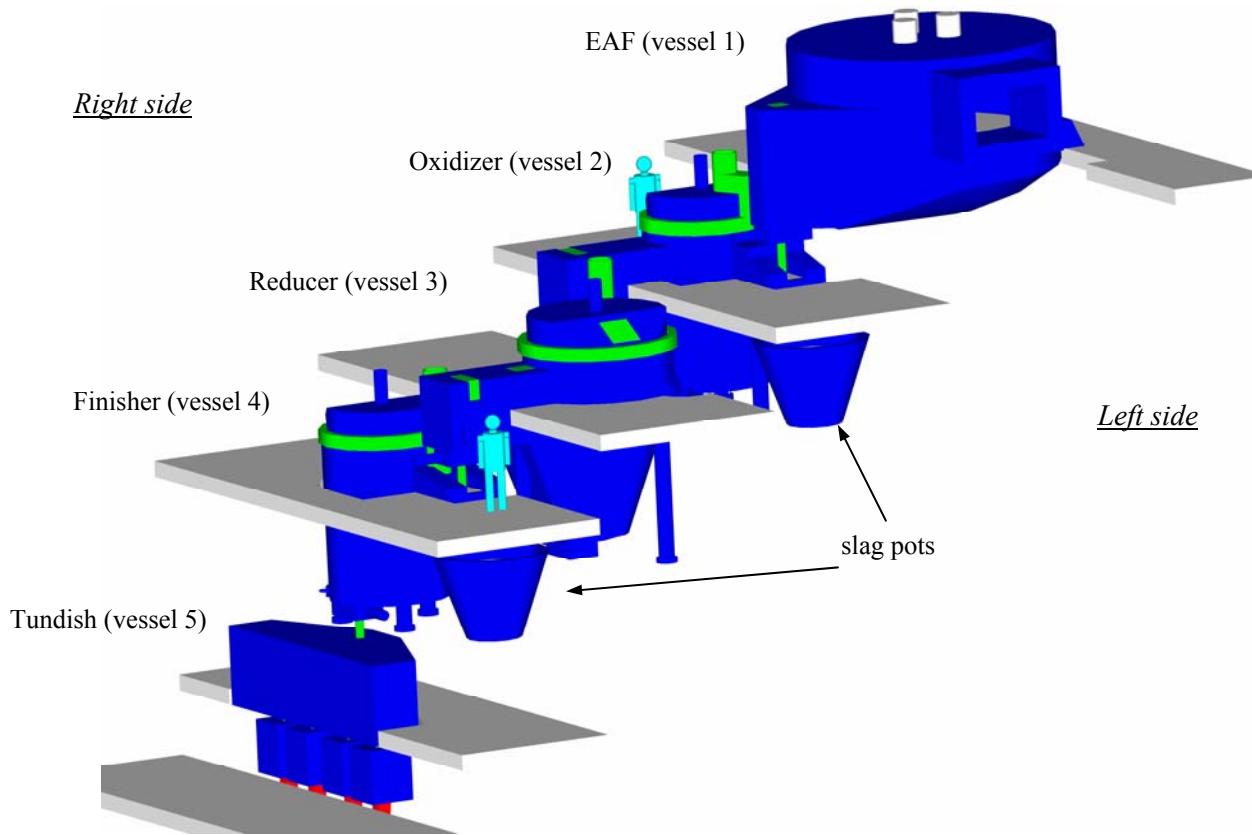


Figure 8: Left-side view of process, showing slag pots and partly-drawn working platforms

The operation of the EAF requires continuous loading of fluxes and scrap on the conveyor and the continuous injection of carbon and oxygen to maintain a constant foamy slag with deslagging out the door. This procedure is not much different from many modern Consteel furnace operations. However, a major difference in the continuous steelmaking design is continuous tapping of liquid metal into the Oxidizer instead of periodical tapping into ladles. The operation of the Consteel EAF in a continuous mode (tapping while melting and refining) was successfully tested at the Gerdau-Ameristeel plant of Charlotte in North Carolina⁴.

Steel leaves the EAF and cascades through the three refining vessels before entering the tundish. The treatment of the steel in each refining vessel will include the periodical addition of fluxes and alloys (every two to three minutes) as well as the continuous removal of the slag through the entry launders into slag pots. The slag pots are designed to hold approximately six tons, requiring replacement every eight hours. The operation of the tundish would be similar to current casting operations except that there would be no ladle changes and therefore no temperature and level fluctuations within the tundish, decreasing turbulence, reoxidation, and improving the cleanliness of the cast steel. Periodic temperature and chemistry measurements will be made to allow sufficient time for corrective action. Continuous temperature and chemistry measurement technologies that are in the process of commercialization^{5, 6} would optimize control of the process. In addition, each of the five vessels works as a thermodynamical buffer due to constant near-equilibrium reactions and the series of reactors provides an opportunity to offset variations through differentiated refining and alloying in each vessel.

Procedures for grade changes

In preparation for a grade change, alloying will be decreased in the Reducer and increased in the Finisher, diluting the alloy concentration in the Reducer. At the same time the superheat will be increased in the EAF to offset heat losses associated with flow interruptions. After the steel temperature in the EAF and Oxidizer is increased, the flow through these two vessels will be temporarily stopped, providing a break between grades. Since there will be no steel flowing into the Reducer, alloying in the Reducer will be completely discontinued as the bath level drops. Steel will be continued to be alloyed in the Finisher until the level in the Reducer has dropped to approximately 13 tons. At this point, the Reducer will be closed and the steel in the Finisher represents the end of the old grade and will be drained similar to the last ladle at a grade change in traditional casting operations. As the Finisher drains, flow will be reopened from the first two vessels to the Reducer and a combination of dilution and increased alloying prepares the steel in the Reducer for the new grade. Once the Finisher is drained, the reopening of the Reducer along with alloy and flux additions at the rate required for the new grade will refill the Finisher with the new grade. The Finisher will be reopened after the steel in the tundish is lowered to minimize the amount of intermix material similar to traditional casting operations. Flow will resume at the normal steady-state rate after the Finisher is completely filled. If the steel temperature would decrease below the necessary superheat before steady-state conditions are reestablished, the steel can be heated in vessels 3 through 5 with a non-contact twin plasma torch³.

In addition, it is possible to make a gradual change between grades. For many downstream applications, head-to-tail variations in a single slab are an issue, and these variations could be controlled by spreading out the grade change over several slabs, gradually increasing or decreasing the alloy additions. This practice could decrease the yield losses over current practices. Nevertheless, it will remain important to control and schedule grade changes to minimize the amount of downgraded intermix material.

Continuous steelmaking has a distinct advantage for companies that cast a variety of grades. Currently, steelmakers are limited in the product by heat size. For example, a steelmaker producing 175 ton heats is limited to casting in multiples of 175 tons. If a customer would like 100 tons of a special chemistry, the steelmaker would need to produce 175 tons due to the batch limitation. A customer ordering 200 tons would require 350 tons of production. There is no limitation to order size with continuous steelmaking, meaning that 100 tons of steel could be produced for a 100-ton order, resulting in efficiency, flexibility, and cost savings that are currently unrealized by batch limitations.

Start up

Prior to start-up, vessels 2 through 5 will be preheated with natural gas burners. To start-up, a bucket of scrap will be charged to supply the EAF with a liquid heel before scrap is transported by conveyor into the EAF. When the steel level in the EAF has reached its nominal height, the scrap supply is temporarily stopped to superheat the steel so that the other vessels can be filled without freezing of the steel.

The EAF slide gate will be opened after the steel is superheated in the EAF, filling the Oxidizer. After the Oxidizer is filled, the steel flow will be stopped until the required steel and slag chemistry is achieved in the Oxidizer. The Reducer will be filled after the Oxidizer is opened and started to operate in a continuous mode. The steel flow will be halted again after the Reducer is filled, repeating the procedure that was practiced during the start-up of the Oxidizer. The same procedure will be applied to the Finisher. After the Finisher is filled, the filling of the tundish will start the fully continuous operation of the whole system. If required, the steel temperature could be adjusted in the tundish, Finisher or Reducer with a non-contact twin plasma torch³ during the start-up procedure.

Shut down

The shut down of the process will start with the halting of the scrap conveyor, causing the steel level in the EAF to decrease while the steel continues to flow through the other vessels. After the EAF is completely drained, the steel level in the Oxidizer will decrease until its exit channel is empty. An overhead crane will lift and tilt the Oxidizer to completely drain the steel through its entry launder into the Reducer. The same procedure will be repeated for the Reducer. The Finisher will be bottom-tapped into the tundish and the tundish into the caster.

General procedures for break-down of vessels or some of their components and for maintenance during operation

Sufficient time to repair most typical furnace delays (conveyor repair, electrode additions, apron cleaning, gunning, etc.) will be available during the operation of the continuous process because the EAF is designed to always operate with a 55-ton liquid heel and because the EAF can be completely drained without tilting the furnace. Therefore steel could still be continuously transferred to the Oxidizer, processed in the refining vessels, and cast without charging any scrap for up to 30 minutes. During the furnace delay, the steel flow in the downstream vessels could be decreased to provide more buffer time (up to one hour) for completing the repair. The allowable variability in the casting speeds depends on the continuous caster. Plugging of strands in a multiple strand continuous caster provides more flexibility on production rates.

If a problem occurs with one of the refining vessels, the flow rate will be decreased in the other vessels and the steel flow in the problem vessel can be stopped for up to 15 minutes while the maintenance is accomplished. For instance, the slag line could be gunned in one of the refining vessels while the steel level is lowered. If a longer delay is encountered, the problem vessel could be exchanged with a preheated spare. Each of the refining vessels 2 through 4 and their slag pots sit on a car that resembles a small ladle car. These units can be moved to the side, making it possible to change each refining vessel on the fly as it is currently practiced during tundish changes. The Oxidizer and the Finisher can be moved to the right side and the Reducer to the left side to be exchanged with their preheated spares. The flow through the upstream vessels would have to be temporarily stopped during the change of the problem vessel. The replacement of refining vessels with their spares can also be used to increase campaign durations by performing maintenance of only one vessel at the time.

FIRST SIMULATION RESULTS

Simulation of steady-state operation

The simulation results and steady-state operation conditions during fully continuous production of Si-deoxidized steel are summarized in Table 1. The simulations were calculated with the process model program Metsim. The Free Energy Minimizer (FEM) of Metsim was adjusted based on thermodynamical calculations, using FactSage. The process models are currently being verified with industrial data⁷. Additional results, dynamic simulations, and model details will be discussed in subsequent publications. For instance, dynamic simulations will provide predictions about effects of Cu contaminations.

The simulation was based on a 110-t/hr production rate. The steel and slag masses and compositions of each vessel, as listed in Table 1, are the result of reactions of the incoming steel stream with alloys, fluxes, and air. The extent of these reactions and the composition of the steel and the slag depend on the mass transfer and thermodynamic conditions within each vessel. The mass transfer rate constant (k) was calculated by using the specific steel transport rate⁷, which is a function of argon flow rate, vessel geometry, steel temperature, and pressure. The thermodynamic conditions in each vessel support fast reactions and the removal of impurities. For instance, the de-S rate is increased when less iron oxide is supplied to the bath⁷. Iron oxide sources that include oxidized carry-over slags, oxidized sculls in ladles, slag from previous heats, and iron oxides from ladle cleaning would be minimized due to less emptying, cleaning, and refilling of vessels and because no EAF carry-over slag will enter the Reducer.

The steel temperatures were calculated during the simulation based on the effects of additions, chemical reactions, and heat losses to the environment. The heat losses correlate to a cooling rate of 1.5°F per minute in ladles. This value was based on estimations of survey data from ladle treatment operations in eight meltshops¹. The data of recent temperature measurements during ladle refining will be evaluated to estimate the energy losses to the environment more accurately. The current simulation results indicate that the steel only needs to be heated in the EAF during steady-state operations. The steel temperature in the EAF was set to be 2940°F. Steel of this temperature entered the Oxidizer where it cooled to 2885°F before entering the Reducer, where it cooled an additional 55°F. The steel that flowed from the Finisher into the tundish had a temperature of 2800°F. In general, the heating in the EAF is sufficient because of short processing times, efficient use of fluxes and alloys due to near-equilibrium conditions, and elimination of tapping into ladles that are below the steady-state temperatures.

Based on modern Consteel operations¹, it is estimated that the melting and heating of 120 tons of scrap per hour in the EAF requires 320 kWh/t electricity and the injection of oxygen at a rate of 2000 scfm. The steel flow from the EAF into the Oxidizer is estimated to be 109 t/hr, assuming a 91% metallic yield in the EAF. The liquid EAF slag has a FeO concentration of 14% and is in close equilibrium with the carbon content of the steel (0.08%) due to steady-state furnace operations. The carbon concentration of the steel in the EAF can be increased as compared to the current EAF-LMF steelmaking route because additional de-C is possible in the Oxidizer.

The carbon and phosphorus concentrations are decreased in the Oxidizer from 0.08% C to 0.04% C and from 0.010% P to 0.003% P due to the addition of 4 lbs of hematite per ton of steel. The concentrations of both elements are increased in the Reducer to 0.06% C and 0.007% P because the ferroalloys contain carbon and phosphorus. The refining conditions change from oxidizing to reducing when the steel flows from vessel 2 into vessel 3. The stirring of the steel and the addition of alloys and fluxes causes the de-S of the steel from 0.050% S to 0.015% S in the Reducer. Additional de-S from 0.015% S to 0.009% S is achieved in the Finisher. Some aluminum reversion was calculated during the refining in the Reducer and Finisher.

Table 1: Example of steady-state operation conditions, flux and alloy additions, and steel and slag chemistries for producing 110 t/hr

EAF (vessel 1)			steel	additions lbs / t	slag	liquid	solid		
			wt%			wt%	wt%		
electricity	320	kWh/t	C	0.08	high Ca lime	74	CaO	52	1
oxygen	2000	scfm	Mn	0.20	dolomitic lime	42	SiO ₂	20	-
scrap	120	t / hr	P	0.010	Ca-Aluminate	-	Al ₂ O ₃	4	-
capacity	55	t	S	0.050	bauxite	-	MgO	5	83
temperature	2940	°F	Si	0	hematite	-	MnO	1	3
total slag	200	lbs/t	Al	0	SiMn	-	FeO _x	14	13
solid slag	4	wt%	V	0	FeSi	-	other	4	-
					FeV	-			

Oxidizer (vessel 2)			steel	additions lbs / t	slag	liquid	solid		
			wt%			wt%	wt%		
capacity	27	t	C	0.04	high Ca lime	3.6	CaO	52	33
flow rate	109	t / hr	Mn	0.18	dolomitic lime	1.0	SiO ₂	11	-
temperature	2885	°F	P	0.003	Ca-Aluminate	-	Al ₂ O ₃	16	-
argon	5	scfm	S	0.050	bauxite	3.0	MgO	6	45
k	0.15	min ⁻¹	Si	0	hematite	4.0	MnO	3	1
total slag	13.4	lbs/t	Al	0	SiMn	-	FeO _x	8	21
solid slag	2	wt%	V	0	FeSi	-	other	4	-
					FeV	-			

Reducer (vessel 3)			steel	additions lbs / t	slag	liquid	solid		
			wt%			wt%	wt%		
capacity	27	t	C	0.06	high Ca lime	6.0	CaO	50	29
flow rate	110	t / hr	Mn	0.90	dolomitic lime	2.0	SiO ₂	18	-
temperature	2830	°F	P	0.007	Ca-Aluminate	5.0	Al ₂ O ₃	15	-
argon	5	scfm	S	0.015	bauxite	-	MgO	7	71
k	0.25	min ⁻¹	Si	0.26	hematite	-	MnO	-	-
total slag	15.2	lbs/t	Al	0.002	SiMn	20.4	FeO _x	-	-
solid slag	2	wt%	V	0	FeSi	3.2	other	10	-
					FeV	-			

Finisher (vessel 4)			steel	additions lbs / t	slag	liquid	solid		
			wt%			wt%	wt%		
capacity	23.5	t	C	0.06	high Ca lime	1.4	CaO	49	12
flow rate	110	t / hr	Mn	0.90	dolomitic lime	-	SiO ₂	11	-
temperature	2800	°F	P	0.007	Ca-Aluminate	2.4	Al ₂ O ₃	24	-
argon	1	scfm	S	0.009	bauxite	-	MgO	8	88
k	0.06	min ⁻¹	Si	0.25	hematite	-	MnO	-	-
total slag	4.0	lbs/t	Al	0.005	SiMn	-	FeO _x	-	-
solid slag	2	wt%	V	0.040	FeSi	-	other	8	-
					FeV	1.0			

Steady-state simulations of upset conditions

The simulation of continuous steelmaking operations was modified during five additional runs of the Metsim model. The final carbon, phosphorus, and sulfur concentrations after these runs are summarized in Table 2. The values of simulation 1 in Table 2 represent the results that were discussed in the previous section and they are used as a baseline for the other simulations.

Table 2: Final carbon, phosphorus, and sulfur concentrations as calculated during six different steady-state simulations

Simulation	1	2	3	4	5	6
Difference to Simulation 1	Baseline	Double production rate	Triple P Double S	Failure of porous plug in the Reducer		
				No actions	de-S in Oxidizer	↑ Ar in Finisher
wt% C	0.06	0.07	0.06	0.06	0.10	0.06
wt% P	0.007	0.014	0.016	0.007	0.019	0.007
wt% S	0.009	0.019	0.018	0.018	0.007	0.011

In simulation 2, the production rate (scrap and alloy addition rate) was changed from 110 t/hr to 220 t/hr without changing the amounts of flux additions or the values of the mass transfer rate constants. The concentrations of carbon, phosphorus, and sulfur increased during simulation 2 as compared to simulation 1; however, they were within common values after ladle refining of Si-deoxidized steel. It is expected that additional simulations will show that a proportional increase of flux additions and the increase of the argon stirring would make it possible to decrease these concentrations to values similar to simulation 1. The result of simulation 2 indicates that it is possible to continuously vary the production rate during the operation of the continuous steelmaking process.

The effect of an initial impurity concentration increase in the scrap without detection was calculated during simulation 3. The phosphorus and sulfur concentrations of the steel that entered the Oxidizer were increased from 0.010% P to 0.030% P and from 0.050% S to 0.100% S without changing other operational conditions of simulation 1. The final sulfur and phosphorus concentration increased; however, they were again within common values after ladle refining of Si-deoxidized steel. This result indicates that final steel chemistry is still within typical steel specifications after undetected P and S increases in the scrap. Once the impurity increase is detected, corrective actions such as an increase in argon flow rate and flux additions could decrease the final P and S to values similar to simulation 1.

A failure of the porous plug in the Reducer was investigated during simulation 4. It was assumed that the swirl that is created in the vessel due to the off-center inlet stream² would still result in a mass transfer rate constant of 0.05 min^{-1} (down from 0.25 min^{-1} during argon stirring). The simulation was calculated without changing other operational conditions of simulation 1. The final sulfur concentration increased to 0.018%, which is a common value after ladle refining of Si-deoxidized steel. This result indicates that a failure of a porous plug would not necessarily lead to a final steel chemistry that is outside the grade specifications.

Two corrective actions of a porous plug failure in the Reducer were investigated during simulations 5 and 6. In simulation 5, the operation of the Oxidizer was modified by replacing the oxidizing slag with a reducing slag and making SiMn and FeSi alloys additions in the Oxidizer. All other operating conditions were the same as during simulation 4. The final sulfur concentration of simulation 5 was lower than the final sulfur concentration of simulation 1 because some sulfur was removed from the steel in all three refining vessels. The final carbon and phosphorus concentrations increased because these elements were not removed in the Oxidizer. Remarkably, the steel chemistry in the Oxidizer during simulation 5 (0.10% C, 0.019% P, 0.018% S) was similar to the final steel composition after ladle refining of Si-deoxidized steel. This result indicates that the steel treatment in only one of the three refining vessels can achieve similar refining to current ladle treatment.

Simulation 6 was similar to simulation 4 with the exception that the gas flow rate and the flux additions were increased in the Finisher, raising the mass transfer rate constant in this vessel to 0.15 min^{-1} . This change decreased the final sulfur concentration from 0.018% S (simulation 4) to 0.011% S while the final carbon and phosphorus concentrations were as low as after simulation 1. The increase of the argon flow rate in the Finisher has the potential to increase the inclusions in the final product due to increased turbulence and slag entrapment. Other corrective actions would also be possible. For instance, the meltshop crew could have chosen to exchange the Reducer on the fly after the porous plug failed.

SUMMARY

A novel, scrap-based, fully continuous steelmaking process has the potential of increasing safety, productivity, quality, and capital utilization while lowering the energy consumption and production cost as compared to traditional EAF-LMF-CC steelmaking. The new process requires significant less space, decreasing the size of the meltshop building to approximately one third of a conventional EAF meltshop.

The new process will make it possible to continuously convert scrap to cast product in less than two hours. The vessels are designed for fast, near-equilibrium reactions to ensure a large degree of control, productivity, flexibility, and to reduce maintenance. The new process has the potential to increase refining and decrease alloy and flux consumptions as compared to current operations and to minimize of variations in fluid flow and composition, ensuring a reliable operation. The production rate can be widely varied (between 70 t/hr and 170 t/hr for this particular design) during continuous operation, giving steelmakers a flexible tool that is able to respond to market demands, maintenance requirements, and unscheduled delays.

Simulations predict that the process can produce quality steel even during unexpected upset conditions in the production. The sudden increase of impurities during melting or a failure of part of the equipment does not necessary lead to a final steel chemistry outside of the grade specifications. The design of the process makes it possible to change grades without increasing the amount of down-graded transition steel when compared to current practices. In addition, continuous steelmaking has the advantage of only producing exactly the order amount of steel, decreasing yield losses associated with current full heat lots.

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