4.
Experimental Procedure

4.1.
Industrial Apparatus

The model coefficients calculation and the validation tests were conducted in a conventional AC electric arc furnace (EAF) of 120 t nominal tap weight with a 112 MVA transformer. The tap-to-tap time of 45 minutes, accounts two buckets charging procedure. The production rate is approximately 130 ton/h. The metallic raw materials are usually composed of ferrous scrap and pig iron. For this investigation purpose, the amount of pig iron was varied from 8% to 49%. All the fluxes were charged into the buckets, and only coke powder was injected during the end of melting and along refining steps. Figure 57 presents schematic cross section of a typical EAF vessel and gas-coke injectors. Oxygen injection, in the range of 31 to 53 Nm^3/t, was carried into the melt pool as well as in the EAF atmosphere. Injection technology consisted of submerged lances at the slag door, oxy-natural gas burners, coherent jet injectors and post combustion injectors located at the water cooled panels on the furnace upper shell. Coke injection was carried out in the range of 2 to 18 kg/t, both by submerged pipes as well by side wall injector upon the slag surface.

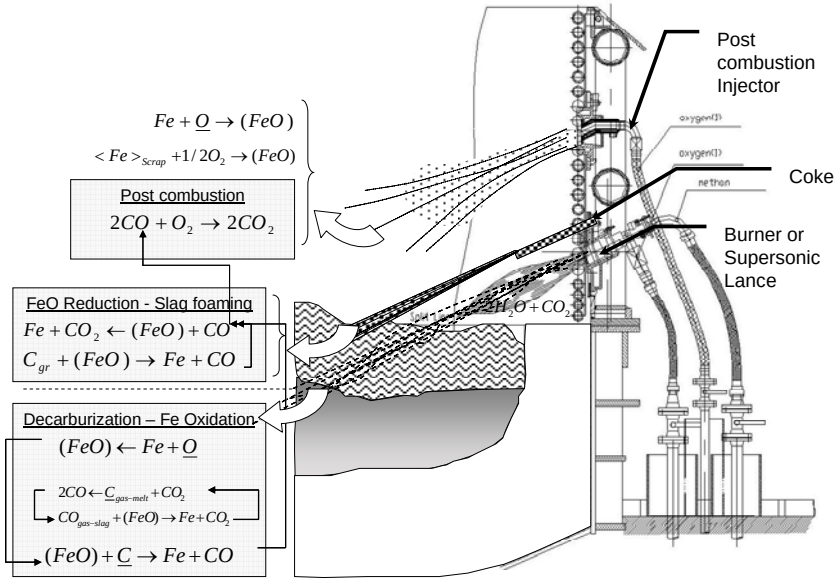


Figure 57 - Example of different oxy-gas-coke injector's applications in EAF

The main roles of the four different injectors can be summarized as follows:

i. Lancing Mode: Oxygen for decarburization purposes mainly, through submerged lances and supersonic coherent oxygen jet;
ii. Foaming mode: carbon for slag foaming purposes, using compressed air for powder transportation and injection. Metal phase recarburization can also occur;
iii. Post combustion Mode: CO combustion above the slag surface, applying low oxygen flow rate. Injectors located not so close to the sill level, some of them above and others in the same height of the lancing mode injectors,
iv. Burning mode: Scrap preheating purposes. Oxygen and natural gas slightly above the stoichiometry ratio;

Thirty four heats were produced and data regarding oxygen, natural gas and injected coke flow rates was collected at every 2 seconds. Lime and dololime were accounted as batch input. Temperature, steel and slag spot samples for chemical analysis were collected whenever it was feasible. During the melting time, no accessible liquid steel pool is usually available for sampling through the slag door or even at the EBT area (eccentric bottom tap hole). Therefore, most of the sample for chemical analysis was collected after 55-60% of total electrical energy consumed, which means metal phase temperature around 1520-1540 ^{o}C and almost at the half of the tap-to-tap time.

According to the experimental design, some heats during a defined period of time in the refining step, were produced without oxygen injection by lancing mode and full coke injection, and others with full oxygen injection by lacing mode and without any coke injection. These contrary conditions were conducted to expose the model to extreme situations. The electrical active power program, fluxes addition and the number of buckets charged were kept reasonably constant.

The amount and the chemical composition of the impurities entrapped in the scrap were estimated based on existent mass balance data, extensively generated and validated by an optimization algorithm developed and provided by the local melt shop. The hot heel and the slag weight, as well the off-gas analysis chemical composition were not available as measured variables for the current experiments.

The current model does not take into account the thermal balance yet, and consequently, no melt temperature is estimate. However, it is expected a minor effect of the temperature in the range of 1550 to 1650 oC on the constant of decarburization rate, since the rate–controlling step is accepted to be not the chemical reaction. The mass transfer of oxygen and carbon, which are the controlling parameters, depends much less on temperature.

4.2. Industrial Experiments – Selecting Relevant Variables

The hot heel amount, metal phase remaining in the EAF vessel previously for batch charge, influences the EAF melting performance. A conventional EAF type, working with typical hot heel around 10-15% of the tapping weight capacity, using intensive burners and post combustion, may show substantial difference in the charge preheating level. Consequently, different scrap melting rates may come up when compared with other EAF using hot heel higher than 50% of the tapping weight capacity.

Besides the hot heel size, it can be said that other variables exert significant effect on the melting rate:

- number of charges and charge layering procedures which interfere on the scrap distribution in the furnace. Similar comment can be made regarding the non-metallic charge like fluxing materials;
- charge dimensions, which means size, shape and density distribution;
- the electrical power in put profile strategies: under or over melting the first charges, increasing or decreasing the hot heel size and temperature;

According to the data presented on section 2 Literature Review and operational background at EAF facilities, Table 16 summarizes a simplified variable deployment, aiming to describe roughly the most relevant variable able to influence on carbon and iron reactions. Charging the raw materials, melting and refining can be stated as the main processing steps.

Table 16 – Most relevant variables affecting the decarburization, iron oxidation, as well iron oxide reduction and re-carburization rates.

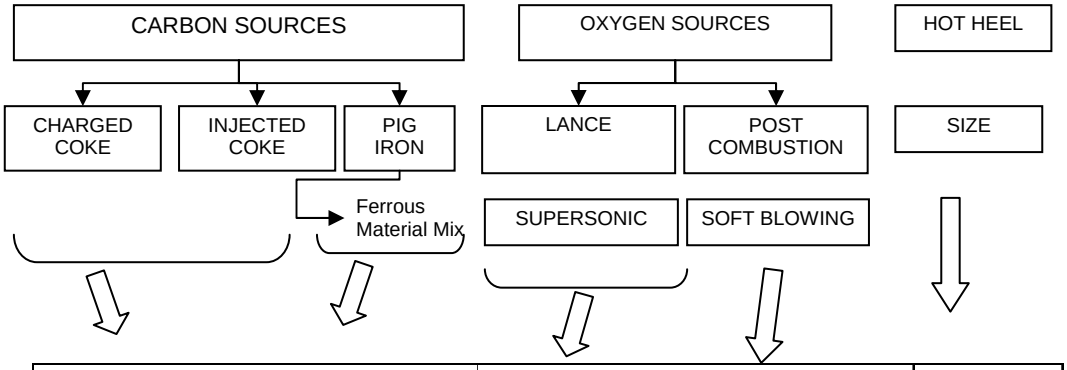
Charging	Ferrous Materials	Batch or Continuous	Dimensional	Size (Area/Volume ratio)	●
				Distribution in the EAF volume	●
			Chemistry	Alloying C,Al, Si,Mn, S, P	●
				Rust (FeO)	●
				Oxides CaO, MgO, SiO2, Al2O3	●
	Slag Formers				●
	Carbonaceous Materials	Charged Coke		C, S, SiO2	○
		Injected Coke			○
Melting & Refining	Melting Rates	Heating, Dissolution and Melting Rates	Electrical power rate	Active Power	○
			Burners power rate	Natural Gas Flow Rate	○
			Alloying elements oxidation	Si, Al and Mn oxidation rates	●
			Post combustion	CO2 Production	●
			Melting temperature		○
			Fluidynamics	Bottom stirring	○
				Electromagnetic stirring	○
				CO stirring	●
			Ferrous materials clustering	Hot Heel Practice	○
			Slag Formers Size and reactivity		○
		Energy Losses	Energy transferring efficiency	Water Cooled Panels	○
				Off-Gas	○
	Carbon and Iron Reactions	Decarburization & FeO Formation	Oxygen flow rate	Lance injection	◍
				Post combustion Injection	◍
			Dissolved carbon content		●
		Recarburization & FeO Reduction	Coke injection	Coke Flow Rate	○
				Coke size and reactivity	○
				Coke Efficiency	○
			Slag Chemistry	Slag basicity	●

● Vary according to the Charge mix (Ferrous Materials) and Slag Formers

◍ Vary according to the oxygen injection setup

○ Assumed constant properties and setup

The number of variables involved and the transient melting period make the EAF steelmaking operation very complex for modeling purposes. In order to minimize such complexity, significant number of variables was managed to be in narrow variation ranges during the experiments. Therefore, carbon and oxygen sources and their input amounts were considered the most important variables. Figure 58 includes also the hot heel size.



CARBON SOURCE				OXYGEN SOURCE				HOT HEEL	
COKE		PIG IRON		LANCE		PCOMB			
kg/ton		% Charge		Nm^3O_2/ton		Nm^3O_2/ton		ton	
2-7	10-20	5-10	30-45	20-25	30-40	0-3	7-10	10-15	20-30

Figure 58 – Grouping variables and defining two levels “bands”

Rearranging Figure 58 resulting in

Table 17, the scheduled experimental conditions tags are distributed over the carbon, oxygen and hot heel variables, grouped in two levels.

Table 17 – Pre-Factorial experiment design. Conditions ID # 1 to 22: (a) Decarburization experiments; (b) Decarburization and deep carbon injection.

				CARBON SOURCE				OXYGEN SOURCE			
				COKE		PIG IRON		LANCE		PCOMB	
				kg/ton		% Charge		Nm^3O_2/ton		Nm^3O_2/ton	
				2-7	10-20	5-10	30-45	20-25	30-40	0-3	7-10
CARBON SOURCE	COKE	kg/ton	5-10								
			10-15								
	PIG IRON	% Charge	5-10	16	3,11,14,18						
			30-45	2,4,6	1,5,17,19						
OXYGEN SOURCE	LANCE	Nm^3O_2/ton	20-25	16	3,17,18,19	3,16,18	17				
			30-40	2,4,6	1,3,5,11,14	11,14	1,2,4,5,6				
	PCOMB	Nm^3O_2/ton	0	16	11,12,18,19	11,16,18	19	16,18,19	11		
			7-10	2,4,6	1,3,5,14,17	3,9,10,14	1,2,4,5,6,17	3,17	1,2,4,5,6,14		
HOT HEEL		ton	10-15	2,6	3,5,14	14	2,4,5,6	3	2,5,6,14	11	2,3,5,6, 14
			20-30	4	1,11,12,17,18	11,16,18	1,17,19	16,17,18	1,4,11	16, 18,19	1,4,17

(a)

				CARBON SOURCE				OXYGEN SOURCE			
				COKE		PIG IRON		LANCE		PCOMB	
				kg/ton		% Charge		Nm^3O_2/ton		Nm^3O_2/ton	
				2-7	10-20	5-10	30-45	20-25	30-40	0-3	7-10
CARBON SOURCE	COKE	kg/ton	5-10								
			10-15								
	PIG IRON	% Charge	5-10	21	9,10,12,20						
			30-45	7,8, 22	13,15						
OXYGEN SOURCE	LANCE	Nm^3O_2/ton	20-25	7,8, 22	12,13,20	12, 20	7,8,13				
			30-40	21	9,10,15	9, 10,21	15				
	PCOMB	Nm^3O_2/ton	0	21, 22	12,15,20	12, 20,21	15	12, 20	11,15,21		
			7-10	7,8	9,10,13	9, 10	7,8,13	7,8,13	9,1		
HOT HEEL		ton	10-15	7,8,21	9,10,20	9,10, 20	7,8,13	7,8,20	9, 10		7,8,9,10
			20-30		12,,13, 15	12	15	12,13,22	15,21	12,15, 20,21	13

(b)

4.2.1. Charging

Batch charging was performed through two buckets of 70 m^3 and 55 m^3. first and second baskets, respectively. The volume of the scrap and substitutes mixes varied according to their densities presented on Table 18. Even though the bucket layering procedures followed the same standard, the mix density varied significantly with the pig iron content. Moreover, the scrap and substitutes mix variation promotes very different C, Si, Al and impurities input too. As a result, the CO and CO_2 formation will also vary accordingly.

Table 18 – Scrap and substitutes properties

	BDL 1	BUSH1	CIRON	FORG	HMS1	HMS2	HMS3	MIU	P&S	PIRON	SHR1	SKU	TURN
Density [t/m3]	1,27	0,65	1,43	1,00	0,85	0,60	0,40	1,19	0,90	3,90	0,90	3,10	0,20
C	0,20	0,07	3,00	0,39	0,27	0,20	0,20	0,25	0,27	4,20	0,15	0,06	0,30
Si	0,25	0,03	0,80	0,25	0,20	0,10	0,10	0,20	0,20	0,70	0,20	0,01	0,15
Mn	0,80	0,37	0,40	0,80	0,60	0,60	0,60	0,60	0,60	0,10	0,70	0,04	0,60
S	0,01	0,02	0,08	0,02	0,03	0,03	0,03	0,03	0,03	0,03	0,01	0,05	0,08
P	0,01	0,02	0,09	0,02	0,03	0,02	0,02	0,02	0,03	0,06	0,01	0,02	0,04
Cu	0,05	0,00	0,40	0,08	0,40	0,35	0,35	0,30	0,40	0,02	0,20	0,23	0,40
Ni	0,04	0,02	0,20	0,05	0,20	0,15	0,15	0,10	0,20	0,01	0,11	0,07	0,30
Cr	0,04	0,03	0,30	0,25	0,30	0,15	0,15	0,08	0,30	0,02	0,10	0,05	0,30
Sn	0,01	0,01	0,03	0,01	0,01	0,10	0,10	0,01	0,01	0,00	0,02	0,03	0,03
Nb	0,00	0,01	0,01	0,01	0,01	0,02	0,02	0,01	0,01	0,00	0,01	0,00	0,00
Mo	0,03	0,00	0,03	0,05	0,00	0,03	0,03	0,00	0,00	0,00	0,01	0,01	0,10
V	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Al	0,01	0,00	0,01	0,00	0,01	0,01	0,01	0,01	0,01	0,00	0,01	0,92	0,00
Zn	0,20	0,37	0,00	0,00	0,37	0,60	0,60	0,00	0,37	0,00	0,00	0,00	0,00
Fe Total	91,62	97,24	89,76	95,56	90,78	88,85	88,85	93,92	92,38	93,36	95,19	80,74	87,00
Fe	91,62	97,24	89,76	95,56	90,78	88,85	84,35	93,92	92,38	93,36	95,19	79,13	87,00

4.2.2.
Slag Formers and Carbonaceous Materials

The properties of slag formers and carbonaceous materials, such as chemical composition, size distribution and reactivity are assumed to be similar for all experiment conditions. Additionally, the injected carbon is assumed to be carried through atmospheric air at a constant flow rate of 150 Nm^3/h.

Electrodes are also considered as a carbon source. The carbon availability rate in slag is presumed proportional to the electrical energy consumption. According to updated electrode consumption model [96], 35% of carbon released through the electrode tip is available to interact with the slag phase.

Table 19 – Properties of slag formers and carbonaceous materials

Slag Formers (%wt)	CaO	MgO	SiO_2	Al_2O_3	CO_2	S	H_2O	Size (mm)
Lime	94.5	0.74	2.2	0.34	2.05	0.02	0.1	10-50
Dololime	56	36	3.9	1.31	2.25	0.04	0.1	10-50

Carbonaceous Materials (%wt)	C_{Fixed}	S	Volatiles	Ash						Size (mm)
				Total	CaO	MgO	SiO_2	Al_2O_3	FeO	
Injected Coke	90.5	0.92	6.2	0.5	0.015	0.005	0.27	0.165	0.025	< 4

4.2.3.
Electrical and Burners Power Rates

The burners were setup at a constant power rate of 2.5 MW each, and the electrical power program was kept the same, providing similar average electrical active power in the range of 63-65 MW for all experimental conditions.

4.2.4.
Post Combustion and Off-Gas

There were no measurements of off-gas flow rate, temperature and chemical composition during the experiments. Therefore, a maximum peak of post combustion at the EAF atmosphere is assumed to reach up to 0.80 whenever there is oxygen available from the Post combustion injectors.

4.2.5.
Melt Stirring and Hot Heel Size

No porous plugs were applied for inert gas stirring purposes. It is presumed that keeping the same electrical power program, the electromagnetic stirring should be considered the same for all experiment conditions.

The pig iron content and the coke injection are supposed to be the more effective variable for promoting melt stirring due to boiling caused by CO evolution.

The hot heel size was evaluated visually, considering the tap hole as the reference line for the metal phase volume estimate. In addition, the ferrous charge weight and billets accounting supported the resident hot heel estimates.

4.2.6.
Gases Injection

Oxygen and natural gas flow rates were measured at every 2 seconds along the heat time considering all injector types.

4.2.7.
Variables Summary and Measurements Methodology

- Table 20 presents a list of variables involved, the way they were obtained or computed:
- Continuous measurements: data available from the automation system and collected at every 2 seconds;
- Single measurement per heat: spot samples collected per heat;
- Single measurement: spot samples collected in a week or in a month, presumed to present similar properties;
- Model computed: Estimated by the process model supported by the generalized reduced gradient algorithm;
- Visual inspection; When the weight measurement is not available, volume is estimated and, consequently, the mass can be also estimated based on the melt density;

Table 20 – Input and output variables managed by the process model

Presumed: Literature data, post combustion ratios, portion not exhausted by the off-gas of slag formers and coke yield.

VARIABLES		Unit	INPUT	OUTPUT
Time	Total Time	hh:mm:ss	Continuous measurement	
	Time - Power On (EAF transformer switched on)	hh:mm:ss	Continuous measurement	
	Time Power Off (EAF transformer switched off)	hh:mm:ss	Continuous measurement	
Gases and Coke Flow Rates	Oxygen Total Flow Rate through Lancing Injectors	Nm3 O2/h	Continuous measurement	
	Oxygen Total Flow Rate through Burners Injectors	Nm3 O2/h	Continuous measurement	
	Natural Gas Total Flow Rate through Lancing Injectors	Nm3 NG/h	Continuous measurement	
	Natural Gas Total Flow Rate through Burners Injectors	Nm3 NG/h	Continuous measurement	
	Total Injected Coke Flow Rate	Kg Coke/min	Continuous measurement	
Electricity	Electricity Consumption	MWh	Continuous measurement	
	Electrical Active Power	MW	Continuous measurement	
	Tension	V	Continuous measurement	
	Current	kA	Continuous measurement	
	Impedance	Ohm	Continuous measurement	
	Arc Stability		Continuous measurement	
Hot Heel	Hot Heel Initial Weight	kg	Visual Inspection	
	Weight Chemical Composition	%	Single measurement per heat	
Fe-Alloys and Losses	Fe-Alloys addition and Slag door losses	kg/t	Presumed	
Weight of Charged Ferrous Material and Tapped Melt Phase	Ferrous Materials Weight per grade and per batch	ton	Single measurement per heat	
	Melt Phase Weight along the heat at any time t	ton		Model Computed
	Metallic Yield along the heat at any time t	%		Model Computed
Ferrous Materials Chemical Composition and Weight	C, Si, Mn, S , P, Al	%	Single measurement	
	Residuais (Cu, Ni, Cr, Sn)	%	Single measurement	
	Rust and Impurities	%	Single measurement	
	Off-Gas dust formation rate	%	Single measurement	
	Density	t/m3	Single measurement	
	Initial Area/Volume Ratio	1/m	Model Computed	
	Charge Weight per batch	ton	Single measurement per heat	
Slag Formers Chemical Composition and Weight	Lime and Dololime Weight at any batch charging	ton	Single measurement per heat	
	Lime and Dololime Yield	%	Presumed	
	Slag Formers Dissolution Rates	kg/min	Presumed	
	Lime and Dololime Chemical Composition	%	Single measurement	
Carbonaceous Materials	Charged Coke Weight	ton	Single measurement per heat	
	Injected Coke Weight	ton	Single measurement per heat	
	Injected Coke Flow Rate	kg/min	Continuous measurement	
	Charged Coke Yield	%	Presumed	
	Injected Coke Yield	%	Presumed	
	Electrode Comsumption Rate	kg/min	Model Computed	
	Constant of Reaction C+FeO (Charged Coke)	kg/min	Model Computed	
	Constant of Reaction C+FeO (Injected Coke)	1/min	Model Computed	
	Coke Chemical Composition	%	Single measurement	
Decarburization Recarburization Iron Oxide Reduction	Critical Carbon	%	Model Computed	
	Minimum Carbon	%	Model Computed	
	Soluble carbon in molten iron in any time t	%		Model Computed
	Oxygen Post Combustion Injector Efficiency Decarburization $OPCE_{Decarb}$	%		Model Computed
Iron Oxidation	Oxygen Lance Efficiency - OLE	%		Model Computed
	Oxygen Post Combustion Injector Efficiency Decarburization $OPCE_{FeO}$	%		Model Computed
Pos Combustão and Off-Gases	Maximum Post Combustion Ratio in EAF atmosphere	%	Presumed	
	Post Combustion in the Slag	%		Model Computed
	CO and CO_2 Formation Rates at any time			Model Computed
	Off-Gas Chemical Composition at any time			Model Computed
Slag	Initial Slag Weight	ton	Presumed	
	Initial Slag Chemical Composition	%	Single measurement per heat	
	Slag Off Rate	kg/min	Model Computed	
	Slag Chemical Composition at any time t (FeO, CaO, SiO2, MgO, P2O5, Al2O3)	%		Model Computed
	Resident Slag Weight at any time			Model Computed
	Iron Weight Losses at any time t	%		Model Computed

4.3.
Laboratory Apparatus – Melting Rates

Complimentary experiments were conducted in laboratory scale by immersing Fe-C alloys cylinders in Fe-C melt. Even though the complexity of EAF conditions is very difficult to be obtained in laboratory, the proposed experiments were designed to reproduce more simple and particular conditions:

- Immersion of single mild steel and pig iron cylindrical samples, individually.
- Immersion of steel and pig iron cylindrical samples wrapped up in steel mesh, simulating composed charges containing solids with very different area to volume ratios.

The main purposes were to observe the chilling effect when preheated and non preheated samples are immersed in melt at different temperatures. Figure 59 to Figure 61 present the basic configuration of the experimental apparatus used in this study.

Resistance furnace:

Lindberg Blue CF 56724 C
Temperature Range 500°C to 1700°C, 5,000 Watts

Process tube:
Alumina: OD 76.2 mm x L915-800 mm
Crucible:
Alumina OD 60 mm x L104 mm (1.28 kg capacity, 30 mm freeboard)

Thermocouple:
Pt 30%Rh- Pt 6%Rh Type B;

Atmosphere:
Nitrogen flow at 0.6 to 1.0 L/min during heating and melt melting;
Open process tube during samples immersion (some oxygen can come in)

Others:
Sample coupling and rod of commercial low carbon steel;

Samples:
Cylinders of steel and pig iron

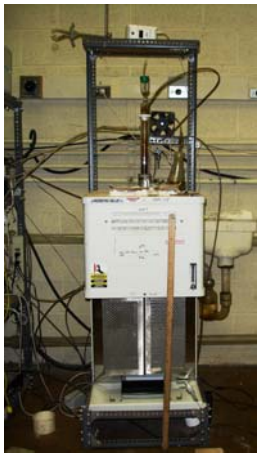


Figure 59 – Lindberg Resistance Furnace

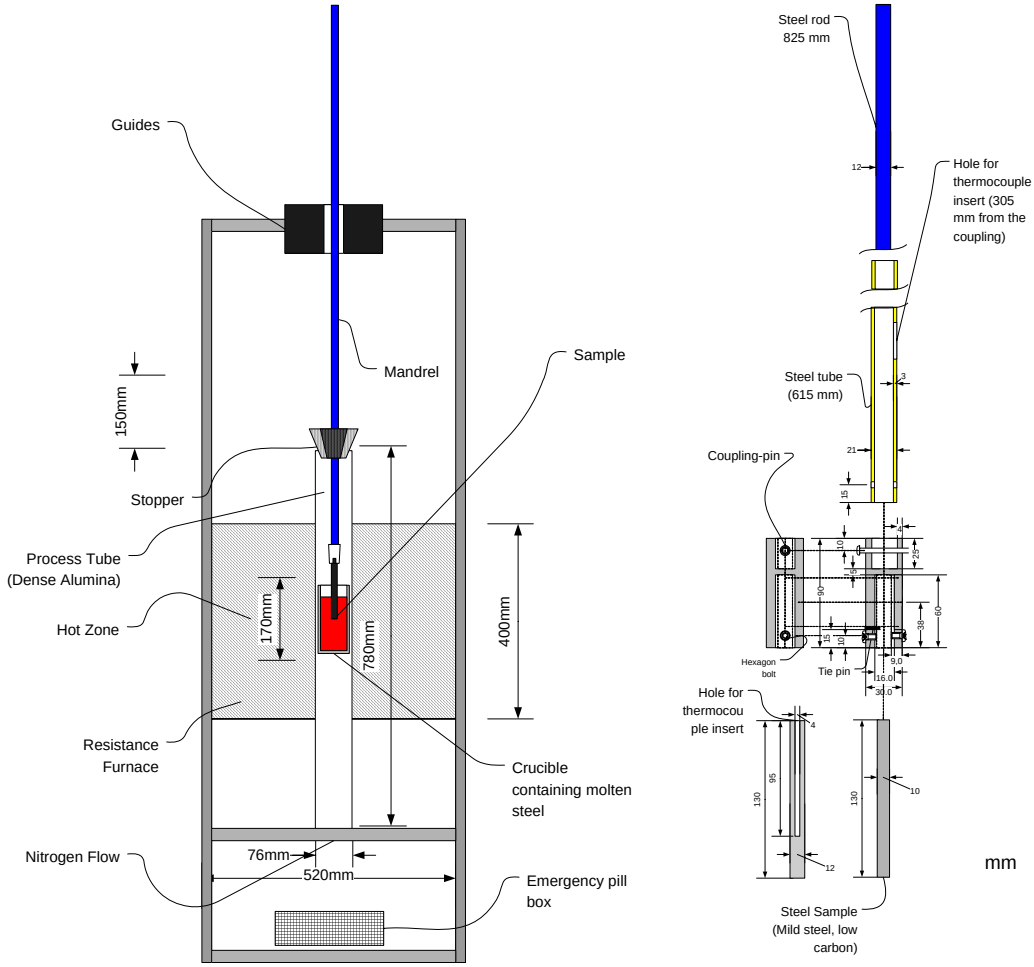


Figure 60 – Apparatus arrangement in a resistance furnace

- Steel rod, coupling and samples were handled manually;
- The top of the process tube was not completely sealed when immersing sample in the melt, because the stopper with 40 mm hole had to be removed to proceed the experiments;
- 1600 ^{o}C was not achieved in the melt due to furnace internal insulation or even the heating elements of the resistance furnace may have lost their former capacities. Therefore, melt temperature were performed in the range of 1440 – 1570 ^{o}C.

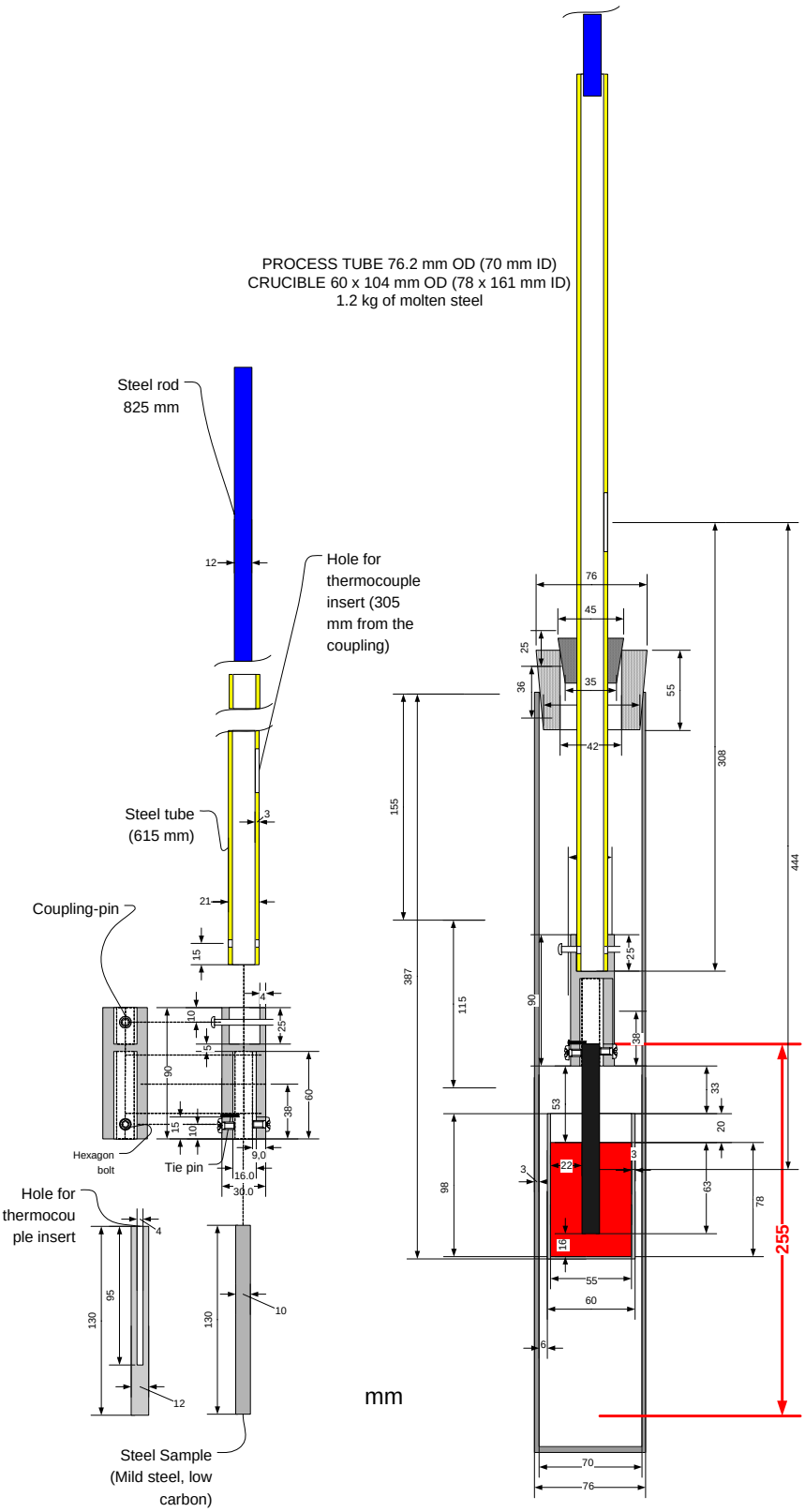


Figure 61 – Details of sample coupling, crucible and process tube dimensions

Pig Iron samples were produced by melting commercial low carbon steel and graphite in an induction furnace under argon atmosphere and MgO crucible. The liquid pig iron was tapped into graphite mold, machined from graphite bars

The temperature profile for three temperature set points was investigated to identify the hot zone of the resistance furnace in order to:

- know the temperature profile in the process tube, checking the best position for the crucible to assure low temperature gradient before immersing samples in the bath;
- estimate the temperature at which the other parts of the apparatus would be exposed to;
- estimate the heating rate of steel samples and the overall heat transfer coefficient.

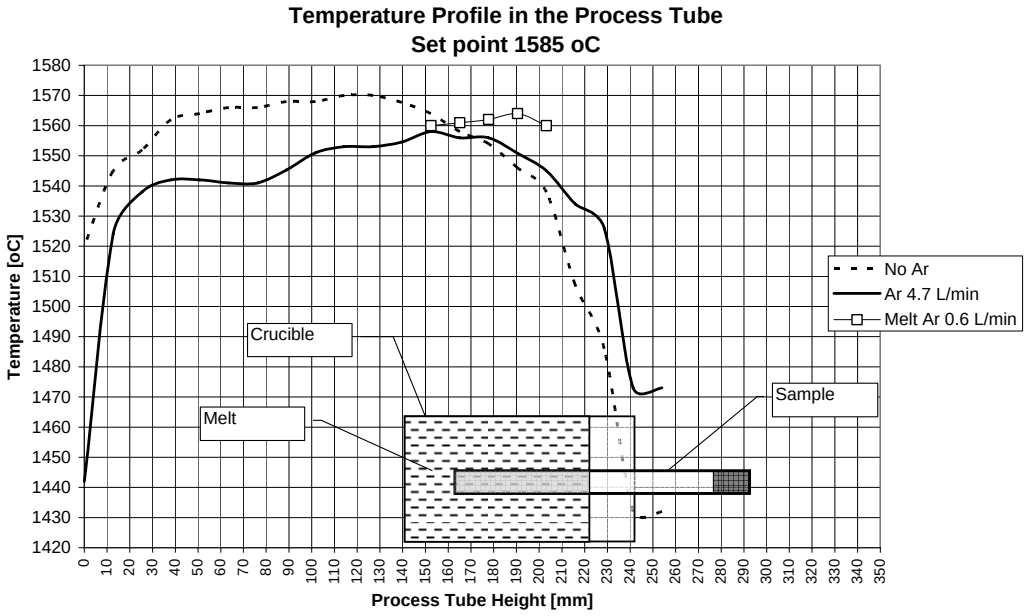


Figure 62 - Temperature profile measured with type B thermocouple at the gas phase in the process tube and in the melt.

According to Figure 62, the bath temperature can be reasonably considered homogeneous before immersing samples. If the samples were not pre-heated, the melt temperature dropped around 10-20 ^{o}C depending on the size of the immersed sample.

Complimentary experiments were conducted using special samples consisting of mild steel or pig iron cylinders wrapped up in steel mesh, according to Figure 63. This special assembling was developed to simulate composite charge of light scrap with high area to volume ratio.

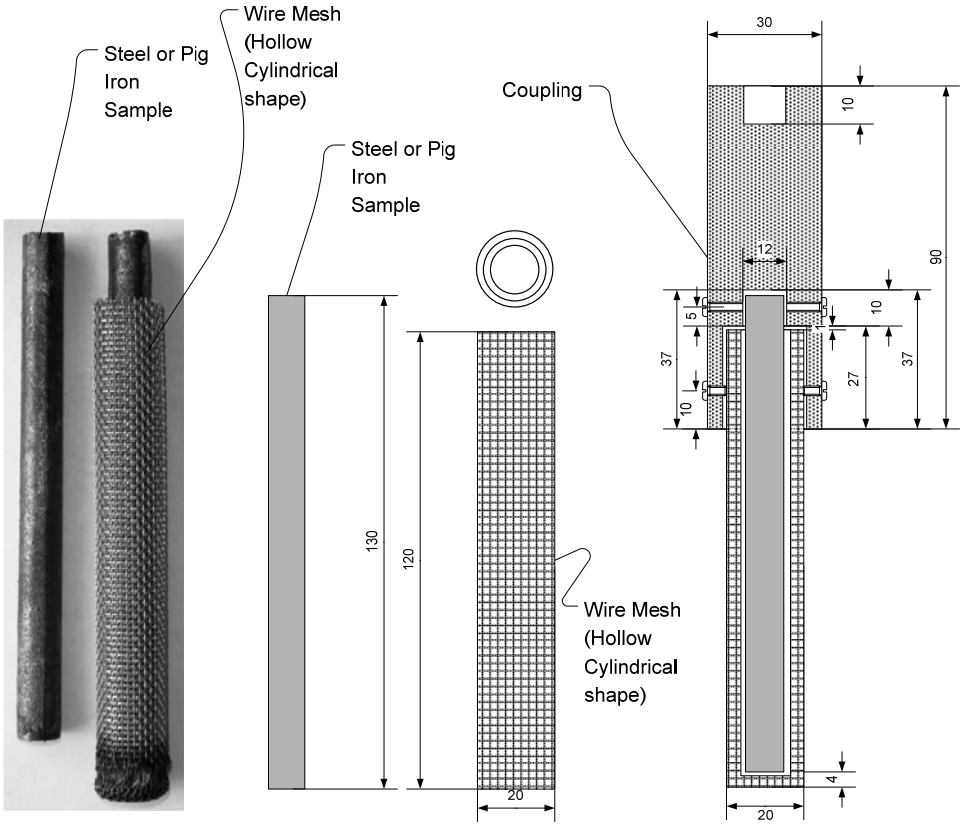


Figure 63 – Steel and pig iron cylindrical samples wrapped up in steel mesh, simulating composed charges.