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ENERGY BALANCE MEASUREMENTS FOR AN ELECTRIC ARC STEELMAKING FURNACE

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The energy and material balance of an electric arc steelmaking furnace are quantified with reference both to the overall tap-to-tap cycle and to furnace operation stages. Each energy input and output is analyzed (assumptions, measurements made, numerical data, etc.). Particular emphasis is given to the study of exothermic reactions by sampling and analyzing exhaust gas dust, as well as to the measurement of shell surface temperatures by infrared thermography.

Les bilans énergétique et matériel d'un four à arc pour la production de l'acier ont été quantifiés en faisant référence à l'entière durée tap-to-tap, aussi bien qu'aux différentes phases de l'opération.
Chaque input et output a été analysé (hypothèses, mesurages, données numériques etc.).
On a étudié l'évolution des réactions ésothermiques au moyen de prélèvements et analyses des poussières des fumées.
On a effectué la détermination des températures superficielles du four au moyen d'une thermographie infrarouge.

Die Bilanz der Energie und des Materials eines Elektrolichtbogenofens für die Stahlherstellung wurde mit Bezug sowohl auf die ganze 'Tap-to-Tap-Dauer', als auch auf die verschiedenen Fertigungsphasen berechnet.
Jedes Energie-Input und Output wurde sorgfältig untersucht (Hypothesen, Abmessungen, numerische Daten u.s.w.).
Eine besonders wichtige Rolle spielt die Untersuchung des Verlaufs der warmabgebenden Reaktionen durch Entnahmen und Analysen der in den Verbrennungsgasen enthaltenen Pulver.
Ebenso wichtig ist die Abmessung der oberflächlichen Temperaturen des Ofenmantels durch die Infrarotthermographie.

1. INTRODUCTION

The design and operation problems of the electric arc steelmaking furnace have been thoroughly investigated but chiefly with regard to the electric parameters and the optimization of the electric operation. On the other hand, also in relationship to the ever-increasing complexity of the furnace system (auxiliary burners, cooling panels, oxygen lances, fume extraction system, etc.), particular attention must be given to the thermal behavior too. In this field, some investigations were made in order to measure and analyze certain individual components of heat loss but not all together. Other studies were concerned with the total heat loss which was not measured directly but determined by drawing up a simplified energy balance (electric input = useful output + heat loss) and measuring the electric quantities only (1).

This paper presents our results in the attempt to set up an experimental methodology to determine all the different energy inputs and outputs simultaneously (no account is taken of the indirect energy inputs (2) related to material consumption and primary energy source conversion).

2. THE ENERGY BALANCE

The equation of energy balance is written for scrap-fed electric arc steelmaking furnaces equipped with auxiliary oxy fuel burners, wall and roof cooling panels, fume extraction from the fourth hole, and in which oxygen lances are used during refining.

The system boundaries are such as to enclose the furnace and allow measurements to be taken at convenient positions.

The principle of energy conservation allows us to make the sum of energy input over an arbitrary time interval equal to the sum of energy output plus any energy storage in the system. Therefore, using the notation illustrated in Fig. 1, we can write the energy balance as :

$$W_{el} + Q_f + Q_c + Q_e + Q_i + Q_{ex} = Q_u + Q_s + Q_g + Q_d + Q_w + Q_h + Q_o + Q_{en} + \sum_i \Delta E_i$$

The energy (and material) inputs and outputs are discontinuous and the system is in non-steady state conditions. Consequently, quantifying each and every balance item would require developing methods capable of measuring not only the energy exchanges across the system boundaries (between the system and the outside environment) but also the time evolution of the storage.

The general equation can be simplified in the case of cyclic operations and if the time interval considered equals the tap-to-tap time, energy storage may be assumed as nil. In this case, by employing the measurement methods described herebelow and within their approximation limits, it is possible to quantify the energy balance for an overall cycle.

When shorter time intervals are considered with reference to the different stages of furnace operation, the above simplification is not possible and the (algebraic) difference between measured input and output energy can be taken as equal to the sum of energy storage.

3. EXPERIMENTAL DETERMINATION OF THE ENERGY BALANCE

The experimental methodology for the direct quantification of the energy balance and for the study of the time evolution of the various balance items was set up and tested in a steelmill equipped with a high power (0.53 MVA/t) arc furnace (technical particulars in Table 1). Measurements were made on several heats between February and June 1983. The results obtained from a specimen heat (no. 931710 of 28 June 1983) will be illustrated in detail further on to clarify procedures and assumptions.

However, the system boundaries should first be defined in order to identify univocally the measurements referring to the various inputs and outputs and the points where these measurements were made. This kind of information is contained in Fig. 2 and Table 2. Special measuring devices were installed but also the existing instrumentation, currently used for process control, was utilized. In particular a new method was employed to determine the inputs originating from the exothermic reactions and the infrared thermography was adopted to quantify the surface heat losses.

4. USE OF INFRARED THERMOGRAPHY

Infrared thermography is a non intrusive temperature measuring method; it is widely used for inspection purposes in various fields and allows to detect qualitatively heat loss and where this occurs. More recently (3), this technique was tentatively used for quantification purposes, and the procedure was improved to reduce its errors and uncertainties. This approach was also taken for the arc furnace with results which appear to be sufficiently accurate.

Thermography allows us to draw a surface temperature map and to follow its evolution in real time. From this map, by suitable heat transfer (convection and radiation) correlations, the surface heat losses are determined.

Fig. 3 shows some examples of thermograms. The first three (Fig. 3-a1, a2 and a3) were taken on a zone of the lower section of the furnace walls; this zone can be assumed as representative of the conditions at the uncooled, refractory-lined wall. The fourth (Fig. 3-b) was taken on a region of the upper section and is representative of the condition of a cooled wall. The surface temperature of cooled wall is nearly uniform and constant, while significant variations of the wall temperature can be noticed in the lower section. Furthermore, as apparent from the thermogram sequence in time (Fig. 3-a1, a2 and a3, referring to melting-down of 1st basket, 2nd basket, and refining stages respectively), the outer surface temperature first decreases and then rises again (the minimum being in correspondence with the melting-down of the 2nd basket).

5. RESULTS OBTAINED FROM A SPECIMEN HEAT

The energy balance quantified from measurements made on the specimen heat is given in Table 3. It can be seen that the data refer both to the overall tap-to-tap cycle (105 min) and to the different stages of furnace operation.

Each energy input and output will be analyzed giving some details about measuring procedures, assumptions made and collection of numerical data (no endothermic reaction will be considered).

5.1 Electricity

Measurements were recorded continuously by the usual instruments available at the steelmill. The measurement point was upstream of the transformer. The electric loss power in the transformer, cables, bus tubes and clamps was taken as a 10% of the readings.

5.2 Oxy Fuel Burners

The burners are fed with a natural gas/oxygen stoichiometric mixture. The comburent consumptions were read at opportune time intervals. Heat of combustion of natural gas at 25°C wa assumed as 34.57 MJ/Nm^3.

5.3 Electrode Combustion

The consumption of graphite electrodes was taken as 4.5 kg/t liquid steel (average value in the considered steelmill); this consumption was distributed over the different stages of furnace operation according to their duration. Heat of combustion of graphite at 25°C was assumed as 32.65 MJ/kg.

5.4 Exothermic Reactions

The main exothermic reactions were considered. Heats of reaction were calculated at a temperature of 1,600°C, with the exception of $C \rightarrow CO_2$, for which 25°C was assumed. The values, in MJ/kg of element, are: $C \rightarrow CO_2$ 31.81; $Fe \rightarrow Fe_3O_4$ 5.90; $Mn \rightarrow MnO$ 7.34; $Si \rightarrow SiO_2$ 28.86; $P \rightarrow P_2O_5$ 23.14; $S \rightarrow SO_2$ 11.26; $Zn \rightarrow ZnO$ 7.12; $Al \rightarrow Al_2O_3$ 28.52.

Samplings and analyses were made with reference to steel scrap, liquid steel, slag and dust in exhaust gases; furthermore, the amounts of different additives were measured. As a result, the material balance of Table 4 was drawn, which allows the complete definition of the quantities of reacted substances in the overall tap-to-tap cycle and in the different stages of furnace operation by adopting the procedure schematically shown in Table 5.

5.5 Steel Heating and Melting

The heat content variation from 25 to 1677°C (tapping temperature) was derived from thermodynamic data and equals 1.394 MJ/kg.

The energy outputs are considered when they cross the system boundaries: according to this criterion, the above output was not distributed over the different stages.

5.6 Slag Heating

The output due to slag heating was evaluated by analyzing slag samples to determine their composition and calculating the heat content variation from 25 to 1677°C: it is equal to 1.905 MJ/kg.

5.7 Cooling Systems

Furnace walls, roof and fume duct cooling systems are composed of a great number of separate elements. In spite of that, both cooling water outlet temperature and flow rate were measured in each loop , since thermocouples reading outlet temperatures have to be located as close as possible to the respective element. Temperatures were continuously recorded. The worked out data are shown in Table 6 grouped in five subsystems.

5.8 Heat Loss: Furnace Shell and Roof Opening

Surface temperature maps were derived from thermographic recordings taken every 10 min. Average temperatures over the different surface regions and the tap-to-tap time were calculated. Finally, by using suitable heat transfer (convection and radiation) correlations, the heat loss components were found out. A breakdown of these by type of surface region is given in Table 7.

5.9 Exhaust Gases and Dust

Gas temperature was continuously recorded. The average flow rate was 80,000 Nm^3/h. In addition to the gas heat content, the dust heat content was considered. Isokinetic samplings were carried out downstream of the cooled fume ducts in order to determine dust quantity and composition.

6. CONCLUSIONS

The measurement campaign allowed a set-up of the experimental methodology to determine the energy balance of an electric arc steelmaking furnace with reference both to the overall tap-to-tap cycle and to the different operation stages.

Values of inputs and outputs measured in the overall tap-to-tap cycle accord satisfactorily together. Therefore it seems possible, when considering the various stages of furnace operation, to assume that the differences between input and output values correspond to an energy storage in the furnace. The thermography also gave information in the same direction (heat storage in the refractory lining) showing the time variations of the outer surface temperatures. Furthermore, the thermography confirmed the significant difference (two orders of magnitude) between the surface heat losses from the cooled regions of the walls and the heat losses from the uncooled, refractory-lined regions.

Finally, the better knowledge attained of the different energy outputs and their variations with time might help us to identify and evaluate direct or indirect (i.e. by heat recovery devices) energy saving measures.

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Table 1 - Some technical particulars of the steelmill investigated

Electric arc furnace	
Make	Tagliaferri
Capacity (t)	95
Shell diameter (m)	5.7
Electrode diameter (m)	0.55
Transformer rating (MVA)	50
Oxy fuel burners: number and power (MW)	2x4
Water cooled wall panels: number and area (m^2)	8x2.76+4x1.89
Water cooled roof panels: number and area (m^2)	10x2.33
Vacuum arc degassing furnace	
Make	Finkl
Electrode diameter (m)	0.30
Transformer rating (MVA)	8
Continuous casting equipment	
Make	INNSE
Type	Vertical
Strand number	4
Semis (square) size (mm)	200÷320
Semis (round) size (mm)	200÷300
Products	Standard and high quality seamless tubes

Table 2 - Details of measurements made (see Fig. 2)

Measurement point	Material/energy input/output	Measured quantity	Measurement method/device	Notes
1	Charge	Weight	Basket weighing	
		Composition	Analysis	
2	Liquid steel	Weight	Ladle weighing	
		Composition	Mass spectrometry	Sampling before tapping
		Temperature	Thermocouple	
2	Slag	Weight	Pot weighing	
		Composition	Plasma spectrometry	Sampling before tapping
			X-ray diffractometry	
3	Electricity	Electrical power and energy	Wattmeter and integrating meter	Continuous recording and readings
4	Oxygen	Vol. flow rate	Gas meter	Continuous readings
5	Surface heat losses	Surface temperat.	Infrared thermography and thermocouple	Recording every 10 min
6		Ambient temperat.	Thermometer	Simultaneously with thermography measurements
		Air velocity	Hot-wire anemometer	
7	Cooling water	Inlet/outlet temperature	Thermocouple	Continuous recording
		Flow rate	Calibrated orifice	Readings at the beginning and the end of tap-to-tap period
8	Exhaust gases	Temperature	Thermocouple	Continuous recording
8'		Velocity	Double Pitot tube	Readings at different stages of furnace operation
8'	Dust	Weight	Isokinetic sampling	Sampling periods corresponding to the different stages of furnace operation
		Composition	Plasma spectrometry	
			X-ray diffractometry	

Table 3 - Energy balance of the electric arc steelmaking furnace tested, with reference to the overall tap-to-tap cycle and to the different stages of furnace operation. Heat no. 931710, June 28th, 1983. Tap weight = 89.895 t

Stage and duration (min)	Tap-to-tap 105	Repairing 4	Charging (1st basket) 4	Melting-down 25	Charging (2nd basket) 3	Melting-down 16	Charging (3rd basket) 5	Melting-down 25	Refining 18	Tapping 5
Input energy (MJ)										
Electrical energy	159,677			47,031		32,882		49,226	30,538	
Natural gas combustion	[illegible],640			3,890		2,333		1,417		
Anthracite combustion	31,937					26,370		1,654	3,913	
Iron oxidation	7,995			1,884		2,198		2,741	1,172	
Other exothermic reactions	14,587			3,239		2,569		1,448	7,331	
Electrode combustion	13,208			3,931		2,516		3,931	2,830	
Total input	235,044			59,975		68,868		60,417	45,784	
Output energy (MJ)										
Liquid steel	125,314									125,314
Slag	13,166									13,166
Water cooling: wall panels	14,562	826	677	3,187	376	1,864	538	2,912	3,204	978
Water cooling: roof panels	14,703	419	98	2,224	120	2,288	192	3,576	4,678	1,108
Water cooling: fume elbow	7,383	102	78	1,936	141	1,004	250	1,985	1,711	176
Water cooling: rotating duct	10,148	116	89	2,512	188	1,732	396	2,707	2,190	218
Water cooling: fume extraction ducting (four sections)	14,735	238	243	3,903	261	2,177	557	3,904	3,112	340
Exhaust gases	33,993	104	79	7,819	345	10,020	233	8,718	6,494	181
Dust (in exhaust gases)	260			36		112		80	32	
Heat losses: furnace shell	1,149	44	44	273	33	175	55	273	197	55
Heat losses: roof opening	4,123		1,348		1,021		1,754			
Heat losses: fume ducting shell	238	9	9	57	7	36	11	57	41	11
Electrical losses: transformer, cables, bus tubes and clamps	15,968	608	608	3,802	456	2,433	760	3,802	2,737	762
Total output	255,742	2,466	3,273	25,749	2,948	21,841	4,746	28,014	24,396	142,309

Table 4- Detail of the material balance of the electric arc furnace tested, with reference to some elements involved in exothermic reactions. Heat no. 931710

Input elements or compounds (kg)	Fe	Mn	Si	P	S	C	Other metals and non metallics	CaO
Steel scrap (charging 1st basket)	47,228	290	104	13	13	147	2,005	
Steel scrap+anthracite+lime (charging 2nd basket)	28,898	239	80	7	7	1,095	474	3,200
Steel scrap+ferrosilicon(charging 3rd basket)	14,899	63	98	6	6	59	569	
Total input	91,025	592	282	26	26	1,301	3,048	3,200

Output elements or compounds (kg)	Fe	Mn	Si	P	S	C	Zn	Al	Other metals	Non metallics	Ca(as CaO)
Liquid steel (tapping)	88,817	323	18	10	21	297	n.d.	n.d.	409		n.d.
Slag (tapping)	795 (1,099)	190 (245)	1,023 (2,188)	n.d.	n.d.	n.d.	-	131 (248)		251	(2,879)
Dust(melting-down 1st basket)	132	12	-	n.d.	n.d.	n.d.	21	-			(16)
Dust(melting-down 2nd basket)	154	19	-	n.d.	n.d.	n.d.	17	-			(125)
Dust(melting-down 3rd basket)	192	34	-	n.d.	n.d.	n.d.	75	-			(102)
Dust(refining)	82	8	-	n.d.	n.d.	n.d.	10	-			(46)
Dust(total)	560 (773)	73 (94)	-	n.d.	n.d.	n.d.	123 (153)	-		139	(289)
Total output	90,172	586	1,041	10	21	297	123	131		799	(3,168)

Notes: n.d. means that the corresponding elements have not been determined; the dash indicates that the measured quantities are not significant; numbers between brackets refer to the oxide of the corresponding element, i.e. F_3O_4, MnO, SiO_2, ZnO, Al_2O_3, CaO; the figure 409 kg for "other metals" in liquid steel includes in particular 72 kg of Ni, 126 kg of Cr, 18 kg of Mo, and 162 kg of Cu. The elemental balance is incomplete for C (inputs from electrodes and natural gas and output with exhaust gases were not considered) and for Si (inputs from refractories and non-metallic materials in scrap were not considered).

For sake of completeness, the material balance of the heat is also given, with reference both to the overall tap-to-tap cycle and to the different stages of furnace operation: input materials: steel scrap 95,200 kg (49,800 + 29,800 + 15,600), anthracite 1,000 kg, lime 3,200 kg, ferro silicon (75% Si) 100 kg; output materials: liquid steel 89,895 kg, slag 6,910 kg dust (in exhaust gases) 1,448 kg (276 + 491 + 511 + 170).

Table 5 - Scheme of the measurements made and procedure adopted for determining the quantities of elements involved in exothermic reactions and their distribution over the different stages of furnace operation

Reaction	Tap-to-tap	Melting-down (1st basket)	Melting-down (2nd basket)	Melting-down (3rd basket)	Refining	Determination of reacted quantities (tap-to-tap) according to	Distribution over the different stages according to
$Fe \rightarrow Fe_3O_4$	I/O	D	D	D	D,S	D+S (≪ I/O)	D,S
$Mn \rightarrow MnO$	I/O	D	D	D	D,S	D+S (≃ I/O)	D,S
$Si \rightarrow SiO_2$	I/O	D(-)	D(-)	D(-)	D(-),S	I/O (≪ S)	I/O
$Zn \rightarrow ZnO$	n.d.	D	D	D	D,S(-)	D	D
$Al \rightarrow Al_2O_3$	n.d.	D(-)	D(-)	D(-)	D(-),S	S	Refining only
$P \rightarrow P_2O_5$	I/O	n.d.	n.d.	n.d.	n.d.	I/O	Refining only
$S \rightarrow SO_2$	I/O	n.d.	n.d.	n.d.	n.d.	I/O	Refining only
$C \rightarrow CO_2$	I/O	n.d.	n.d.	n.d.	n.d.	I/O	I/O (^)

Notes : n.d. means that the corresponding elements have not been determined; the dash (-) indicates that the measured quantities are not significant; I/O refers to the difference between input quantities in steel scrap and additives and output quantities in liquid steel; S refers to measurements in slag; D refers to measurements in dust.

(^) As regards the $C \rightarrow CO_2$ reaction the following assumptions were made: max. carbon content in the liquid steel after melting-down of the 2nd basket (anthracite charging) is 0.55%; carbon from electrodes and natural gas does not affect the liquid steel composition.

Table 6 - Details concerning water cooling of the electric arc furnace tested, with reference to the overall tap-to-tap cycle and to the different stages of furnace operation. Heat no. 931710

Water cooling	Water flow rate (m^3/h)	Average inlet/outlet temperature difference (°C, upper line) and heat transfer (MW, lower line)									
		Tap-to-tap	Repairing	Charging (1st basket)	Melting-down	Charging (2nd basket)	Melting-down	Charging (3rd basket)	Melting-down	Refining	Tapping
Wall panels	315	6.3 2.31	9.4 3.44	7.7 2.82	5.8 2.12	5.7 2.09	5.3 1.94	4.9 1.79	5.3 1.94	8.1 2.97	8.9 3.26
Roof panels	250	8.0 2.33	6.0 1.75	1.4 0.41	5.1 1.48	2.3 0.67	8.2 2.39	2.2 0.64	8.2 2.39	14.9 4.33	12.7 3.69
Fume elbow	140.5	7.1 1.16	2.6 0.43	1.9 0.31	7.8 1.28	4.8 0.79	6.3 1.03	5.1 0.83	8.1 1.33	9.7 1.59	3.6 0.59
Rotating duct	160	8.6 1.60	2.6 0.48	1.9 0.35	8.9 1.65	5.6 1.04	9.6 1.78	7.1 1.32	9.7 1.80	10.9 2.03	3.9 0.72
Fume ducting (four sections)	252	8.2 2.40	3.5 1.02	3.4 1.00	9.1 2.67	4.9 1.43	8.0 2.34	6.3 1.85	8.9 2.61	10.2 3.00	3.9 1.14

Note : Inlet temperatures were in the range 29.0 - 33.6 °C.

Table 7 - Details concerning surface heat losses for individual areas of the electric arc furnace tested and for the overall tap-to-tap cycle. Heat no. 931710

Surface region	Water cooling	Surface area (m^2)	Average temperature (°C)	Convection heat loss (kW)	Radiation heat loss (kW)	Total heat loss (MJ)	(%)
Walls	Yes	36.8	42 (m)	2	3	31.5	2.3
Roof	Yes	28.8	45 (e)	2	3	31.5	2.3
Fume ducting	Yes	41.6	45 (e)	3	5	50.4	3.6
Walls	Not	23.6	238 (m)	33	72	661.5	47.7
Roof	Not	3.7	250 (e)	8	14	138.6	10.0
Bottom	Not	41.4	115 (m)	14	31	283.5	20.4
Fume ducting	Not	10.1	180 (e)	12	18	189,0	13.7
Total of furnace+ + fume ducting						1,386.0	100.0

Notes: Temperature values are space and time averages; (m) applies to measured values and (e) applies to estimated values. Ambient temperature was 27°C.

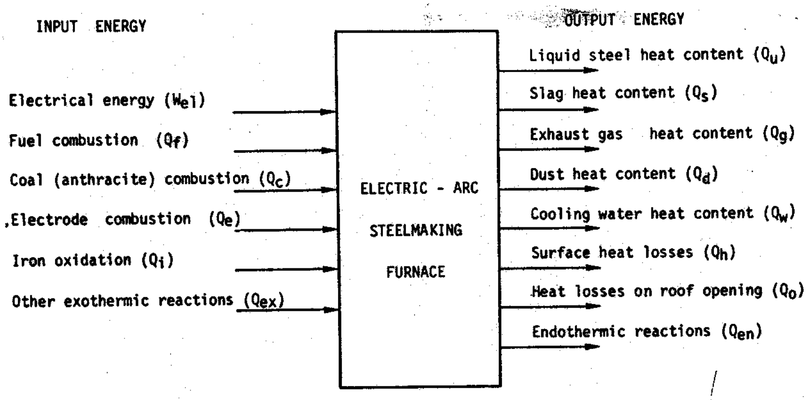

Fig. 1 - Energy balance scheme for an electric arc steelmaking furnace

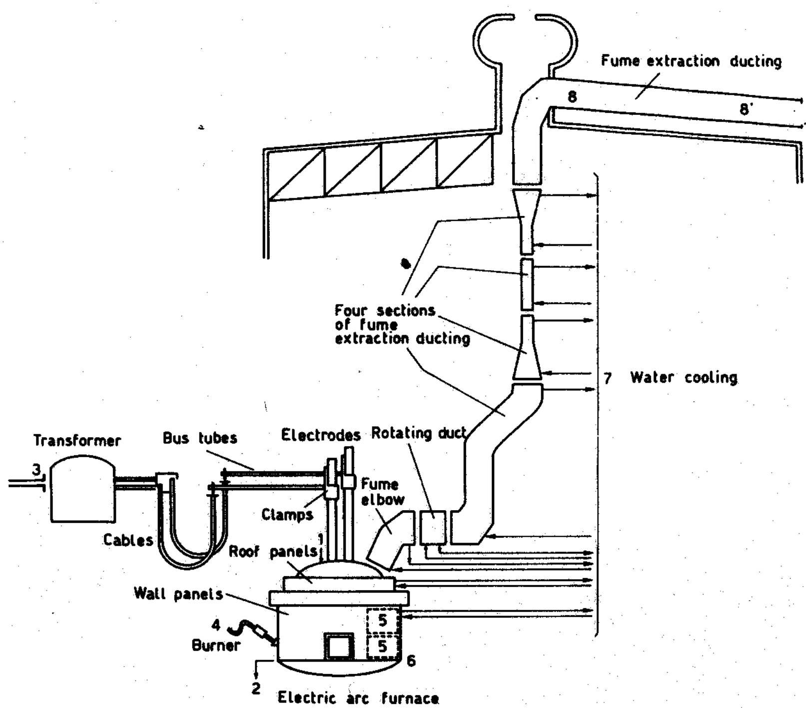

Fig. 2 - General arrangement of the electric arc furnace tested: numbers state positions of measurements made (see Table 2)

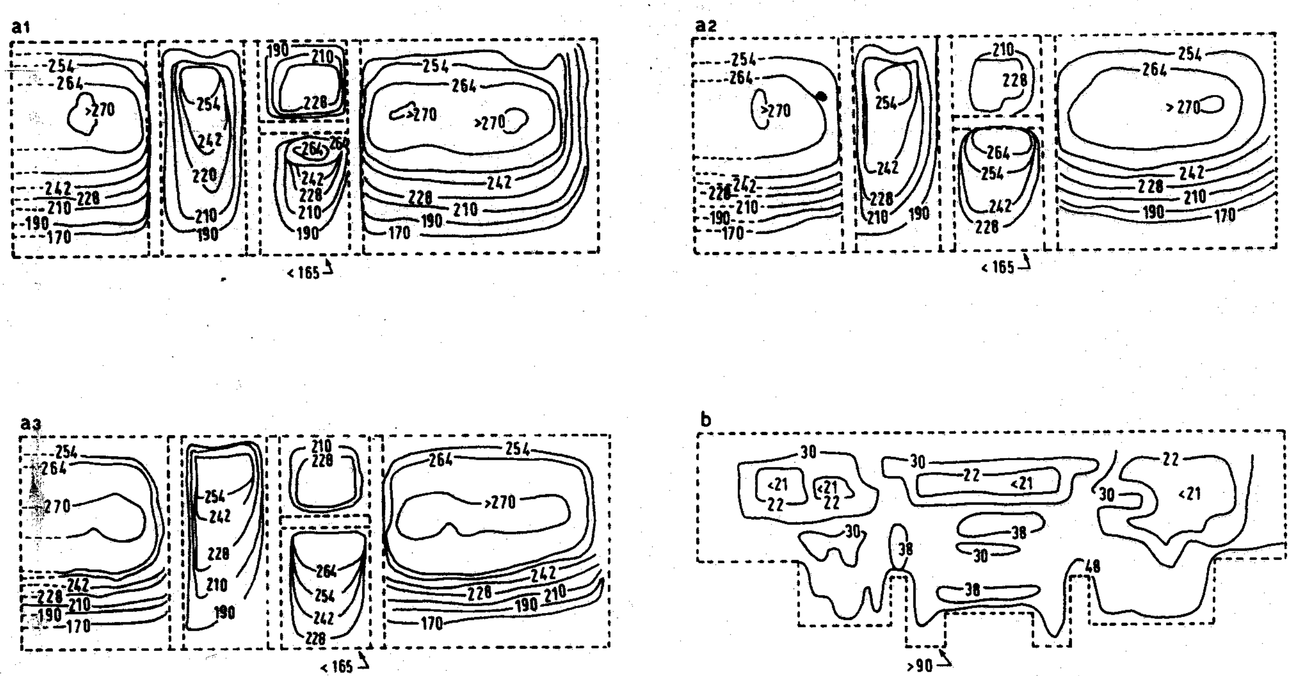

Fig. 3 - Some examples of thermograms taken on the sidewalls of the electric arc furnace tested: letters a and b refer to uncooled and cooled regions respectively; numbers 1, 2 and 3 refer to melting-down 1st basket, melting-down 2nd basket and refining stages; data collected by the thermographic instrument were converted into temperatures in °C