

Ben Bowman | Klaus Krüger

Arc Furnace Physics



Contents

1	Arc generalities	1
1.1	General arc physics	1
1.2	Introduction to industrial arcs	2
1.3	Sources of information on arcs	2
2	DC graphite electrode laboratory arcs	5
2.1	Arc stability	5
2.2	The plasma jet	5
2.3	Measurements of arc thrust	6
2.4	Mass flow rate	8
2.5	Arc voltage and voltage gradient	8
2.6	Arc shape	10
2.7	Power balance at the cathode spot	11
2.8	Current density and time constant of the cathode spot	13
2.9	Convective power of the cathode jet	13
2.10	Radiation	14
2.11	Power balance distribution between convection and radiation	15
2.12	Temperature profiles	17
2.13	Summary: The structure and power balance of the DC graphite arc	19
3	Furnace arcs	20
3.1	AC arcs	20
3.1.1	Generalities	20
3.1.2	High speed photos of AC arcs	21
3.1.3	Arc voltage waveforms	23
3.1.4	<i>Analysis of correlated electrical and high speed photographic records</i>	25
3.1.5	Effect of ambient temperature on the arc voltage waveform	26
3.1.6	Diffuse arcs	28
3.1.7	Waveforms recorded on large arc furnaces	28
3.1.8	Arc lengthening measurements	30
3.1.9	Voltage gradients in extremely long arcs in air	31
3.1.10	Radiation measurements from arc and flame	32
3.1.11	Arc flames	32
3.1.12	Summary of measurements on AC arcs	33
3.2	Measurements on DC arcs in furnaces	34
3.2.1	Voltage gradients	34
3.2.2	Arc shape	35

3.2.3	Arc voltage/length relationship	35
3.2.4	Arc voltage and current	36
3.2.5	Average values	37
4	Electrical conductivity, radiation and temperature in furnace arcs	38
4.1	Measurements of arc temperature	38
4.2	Plasma composition in steelmaking furnaces	38
4.2.1	Plasma composition for an arc buried in foaming slag	40
4.3	The electron density and the electrical conductivity	41
4.3.1	Electron density of plasma containing iron vapour	41
4.3.2	Electron density for an arc covered by foaming slag	41
4.3.3	Electrical conductivity	41
4.4	Estimate of arc diameters from conductivity	44
4.5	Radiation in high current arcs	44
4.5.1	Radiation from neutral atoms	44
4.5.2	Radiation from ions and electrons	45
4.5.3	Free-bound radiation	45
4.5.4	Optically thin and optically thick plasmas	45
4.5.5	Radiation from plasmas containing iron vapour	46
4.6	Radiation based estimation of the plasma temperature	52
4.6.1	Theoretical estimates of axial temperature	52
4.6.2	Temperature gradients due to radiation diffusion	52
4.7	Radiation loss from large diameter arcs	53
4.8	An 'explanation' for the voltage gradient	55
4.9	Conclusions concerning radiation power of furnace arcs	55
5	Arc terminations in steelmaking furnaces	56
5.1	Measurements of current density for graphite and steel terminations	56
5.2	Power balance at the anode spot on graphite	58
5.3	Analysis of the spots on steel terminations	59
5.4	Electrode consumption data for short duration arcs on graphite and steel	60
5.5	Power balance at the electrode spots on solid steel	61
5.6	The cathode spot on liquid steel	63
6	Magnetic fields and forces in arc furnaces	64
6.1	Magnetic force on AC furnace arcs and electrodes	64
6.1.1	Magnetic force on the arc due to a finite sized liquid steel bath	66

6.1.2	Summary of fields	67
6.1.3	Deflection during scrap boredown	68
6.2	Magnetic force on the arc in a mono-electrode DC furnace	68
6.2.1	Arc deflection correction for mono-electrode DC	69
6.2.2	Boredown	70
6.3	Conclusion on arc deflection	70
6.4	The Lorentz force in a bent arc column	70
6.5	Skin and proximity effects	71
6.6	Magnetic field shielding due to scrap	72
6.7	Proximity effect in furnace electrodes	74
6.8	Torque on electrodes in an AC furnace	75
6.9	Magnetic fields around AC and DC furnaces	75
7	Arc instabilities	77
7.1	Observed arc instabilities	77
7.2	Reasons for arc movement	77
7.2.1	Instability due to cathode spot 'crater' growth	78
7.2.2	Asymmetrical conductivity near the cathode spot	78
7.2.3	Arc jumping over pieces of scrap	78
7.2.4	The scrap termination effect	79
7.2.5	Effect of DC tip shape	80
7.2.6	Arc plasma instabilities	80
7.3	The helical rotation of the arc column	80
7.3.1	Frequency of arc rotation	81
7.3.2	Instability of very long arcs	81
7.4	Aerodynamic instabilities	81
7.4.1	Reynold's number for an arc	81
7.4.2	Turbulence in the arc column	82
7.4.3	The stabilising effect of the plasma jet	83
7.5	Rates of change of arc voltage in AC furnaces	84
7.6	Effect of slag	85
8	The electric circuit of arc furnaces	86
8.1	The AC circuit	86
8.1.1	Magnetic fields and reactance	88
8.1.2	Reactance in the three-phase circuit	89
8.1.3	Effective phase reactance of a three-phase circuit	89
8.1.4	Reactance calculation	90
8.1.5	Equivalent reactance	91

8.1.6	Measurement of phase reactance	92
8.1.7	Actual furnace reactances	93
8.2	The DC arc furnace power circuit	93
8.2.1	Six-pulse rectifier system	93
8.2.2	Line current in a 12-pulse system	96
8.2.3	18-pulse and 24-pulse systems	97
8.2.4	Electrical characteristics of the DC furnace	98
8.2.5	Active-reactive power characteristic	98
9	Electrical performance of the arc furnace circuit	100
9.1	Measurable parameters	100
9.1.1	Voltage and current	100
9.1.2	Power	101
9.1.3	Three-phase induction meters	101
9.1.4	Definition and measurement of reactive power	102
9.1.5	Measurement of reactive power with a kVarh meter when harmonics exist	102
9.1.6	Alternative definition of reactive power	103
9.2	The measurement of arc voltage	103
9.2.1	Magnitude of the induced error voltage	104
9.2.2	Effect of mast height variations	105
9.2.3	Variables that affect performance	106
9.2.4	Effect of unsteady arc voltage	107
9.2.5	Effect of power factor on current waveform	108
9.3	The three-phase arc furnace circuit	109
9.3.1	The third harmonic	109
9.3.2	Easier passage through current zero	110
9.4	Electrical characteristics during operation	110
9.4.1	Establishing the arcs	110
9.4.2	Variation of parameters through a heat	111
9.4.3	Electrical measurements on arc furnaces: dimensionless relations	111
9.4.4	Relationship between active and reactive power	114
9.5	Unbalanced conditions in the three-phase AC circuit	115
9.5.1	Range of arc voltage and current imbalance	116
9.5.2	The three-dimensional operating space of arc voltage	118
9.6	Modelling of the electrical operation	118
9.6.1	Arc as a linear ohmic resistance	118
9.6.2	Rectangular arc voltage waveform	119
9.6.3	Cassie (circuit breaker) models	120
9.6.4	Arc voltage as a system of harmonics	121
9.6.5	The 'operating or arc reactance' model	123

9.6.6	The measurement and definition of operating reactance	124
9.6.7	The measurement of the 'arc reactance'	125
9.6.8	Relation of operating reactance to power factor	126
9.6.9	An empirical link between the arc reactance and the arc resistance	126
9.6.10	Asymmetrical arc voltage swings with harmonics	126
9.6.11	Misfiring	128
9.7	Summary	128
10	Physical characteristics of steel scrap	129
10.1	A tube model for scrap	129
10.1.1	Packing characteristics	129
10.1.2	Tubes	130
10.1.3	Number of contacting neighbours	130
10.1.4	Current flow between pieces	130
10.1.5	Contact shape and pressure	131
10.1.6	Resistance	131
10.1.7	The effective resistivity of scrap consisting of tubes	134
10.2	Results using the tube model	134
10.2.1	Effect of scrap size and aspect ratio	134
10.2.2	The effect of temperature on effective resistivity	135
10.2.3	Magnetic properties of scrap	135
10.2.4	The skin depth in scrap	137
10.2.5	Application to other shapes of scrap	138
10.3	DC furnaces	138
10.4	Scrap impedance	138
11	The meltdown process	140
11.1	Heat transfer arc to charge	140
11.1.1	Partition of melting time: Arcing directly to scrap or to liquid	140
11.1.2	Heat transfer to solid steel arc terminations	140
11.1.3	Heating by the impact of the plasma jet	141
11.1.4	Normal impact of the arc against a steel plate	142
11.1.5	Heat transfer from an angled arc plasma jet	144
11.1.6	Heat transfer to a bar	145
11.1.7	Summary of heat transfer to a steel plate	146
11.1.8	Radiation exchange between the arc and the charge	146
11.2	Heat transfer from arc to liquid	146
11.2.1	Jet impact onto a liquid	146

11.2.2	Jet impact onto a liquid covered with a lighter layer ('slag covered steel')	147
11.3	<i>Splashing by the arc as a heat transfer mechanism</i>	147
11.3.1	Splash modes	148
11.3.2	Splashing rates	148
11.3.3	Splash distribution and momentum	149
11.3.4	Size distribution of splash drops	150
11.3.5	Splashing by an arc	150
11.3.6	Liquid depression transient	151
11.3.7	Splashing due to a mobile arc	151
11.3.8	Splash rates due to the arc	153
11.3.9	Heat transfer due to splashing	154
11.4	The general scrap meltdown pattern	154
11.4.1	Process stages	154
11.4.2	Diameter of the boredown pit	155
12	Liquid bath phenomena	158
12.1	Stirring in arc furnaces	158
12.1.1	Current distribution and self-magnetic stirring	158
12.1.2	Stirring by the current in DC furnaces	158
12.1.2	Velocity measurements in electromagnetically pumped liquid metals	159
12.2	Stirring forces	160
12.2.1	Lorentz force in AC furnaces	160
12.2.2	Lorentz force in DC furnaces	161
12.2.3	Comments on Lorentz force for AC and DC	162
12.3	Stirring due to arc jet	162
12.4	Heat transfer due to electromagnetic pumping	163
12.5	Depressions in the liquid due to the arc jet	163
12.6	Electrode lifting from short circuit	164
12.7	Lifting of the bath surface by CO bubbles	165
12.8	Effect of CO bubbles on arc length	166
13	Slag effects in arc furnaces	167
13.1	Effect on arc stability	167
13.2	The effect of foaming slag on furnace operation	167
13.3	Detection of arc burial by foaming slag	168
13.3.1	Reference signal	169
13.3.2	Thermal status of water-cooled panels	169
13.3.3	Bath level measurement	169
13.3.4	Light emission	169

13.3.5	Electrical characteristics	170
13.3.6	Sound emission	171
13.3.7	Vibrations of the furnace shell	171
13.3.8	Use of the slag signal	172
13.4	Slag coating on water-cooled panels	172
13.5	Slag properties and arc existence	173
13.6	Current through foaming slag	175
14	Mechanics of the secondary system	176
14.1	Vibrations and damping	176
14.2	Forced vibrations of an electrode column	177
14.2.1	Natural (Eigen-) frequencies	178
14.2.2	Response of the column to a cyclic driving force	178
14.3	Electromagnetically forced vibrations of the secondary system	179
14.3.1	Magnitude of the electromagnetic forces	180
14.3.2	Deflection of the electrode/arm/mast system	182
14.3.3	Response of the electrode/arm/mast system to cyclic forces	182
14.3.4	Calculated resonant frequencies	183
14.3.5	Resonant frequencies measured on arc furnaces	183
14.3.6	Rotation of the electrode tip	185
14.4	Forces occurring during furnace operation	185
14.4.1	Examples of forces generated during scrap melting	185
14.4.2	Resonant conditions observed on some arc furnaces	186
14.4.3	Avoidance of resonance	187
14.4.4	Comments on modes of vibration	187
14.5	Vibrations due to movement of the mast	187
14.5.1	Electrode arm vibrations	187
14.5.2	Hydraulic system vibrations	188
14.6	Motion of the secondary of DC furnaces	190
14.7	Secondary mechanics and regulation	190
15	Power control of arc furnaces	191
15.1	Electrode regulation	191
15.1.1	General requirements	191
15.1.2	Controlled System	193
15.1.3	The importance of secondary dynamics	195
15.1.4	Controlled variable	196
15.1.5	Control strategy	198
15.2	Optimising electrode movements	200

15.2.1	A criterion for judging regulation performance	200
15.2.2	A computer model	200
15.3	Superposed power control	202
15.3.1	Transformer tap control	203
15.3.2	Reactor tap control	205
15.4	Ladle Furnace requirements of the regulation system	206
16	Heat transfer properties of fume in the arc furnace	208
16.1	Fume formation mechanisms	208
16.2	Fume generation rates in steelmaking furnaces	209
16.2.1	Identity of fume particles inside the arc furnace	210
16.2.2	Size distribution of fume particles	211
16.2.3	Fume generated by hand held metal cutting tools	212
16.2.4	Sectional area of fume	213
16.3	Absorption and scattering of radiation by fume	214
16.3.1	Absorption efficiency and depth	214
16.3.2	Significance of absorption and extinction depths	216
16.3.3	Role of fume in heat transfer	216
16.4	Power transfer bath to furnace without fume	217
16.5	Heat transfer during foaming slag or DRI operation, with/without post combustion	217
17	Noise from arc furnaces	220
17.1	Loudness and power	220
17.2	Sound emission of AC furnaces	221
17.2.1	Measurements around arc furnaces	221
17.2.2	Measurements of sound pressure level near furnaces	222
17.2.3	Total power emitted outside the furnace	222
17.2.4	Acoustic power within the furnace	223
17.3	Sound emission of DC furnaces	223
17.4	Mechanisms of noise generation	224
17.4.1	Acoustic model	224
17.4.2	Reduction of noise through the heat	225
17.4.3	Noise in the harmonics of the AC furnace (pulsating cylinder)	226
17.4.4	Sound emission due to sideways displacements of the arc	227
17.4.4	Broadband noise	227
17.4.5	Turbulent jet noise	228
17.4.6	Influence of the electrical operating point	229
17.5	Acoustic power in the meltshop	230

18	References	231
19	Appendix	243
19.1	Properties of steel	243
19.2	Properties of graphite	244
19.3	References (Appendix)	245