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SOME ASPECTS OF SUBMERGED ARC FURNACE START-UP

L. Shu, W. Dai
Jilin Ferroalloy Works, China

ABSTRACT

Furnace start up is an essential operation for ferroalloy producers. Startup procedure and some key operations are discussed in the paper. It also gives the mass and energy balances in startup periods based on the production data. It indicates that proper operation may reduce the energy consumption and shorten the startup duration. Special care must be taken to deal with electrode baking in the stage *at this stage*. Some empirical formulas for furnace startup are presented to evaluate the economy and to estimate the durations, the charging rate and the schedule of first tapping. Metal chemistry control is discussed in the paper. It also describes the operation of the direct startup.

INTRODUCTION

Furnace start-up is of primary concern for the submerged-arc furnace technique. Ferroalloys production of many plants varies with seasons and market. Due to a shortage of electricity supply, furnace shutdowns and startups are quite frequent in some places in China. For example, the 26 furnaces of Jilin Ferroalloys Works were started up 69 times in 1988. This consumed 24 million KWh of extra energy. Therefore, great attention has to been paid to the operation in order to improve the economical results [1,2].

In order to evaluate the operation, the following expression is defined to calculate the electricity consumption at this stage.

$$Wh = Wt - H*T \quad (KWh) \tag{1}$$

where Wh is defined as electricity consumption of a furnace start-up, Wt is the total electricity consumption in the defined duration, H is the specific consumption of the product in KWh/t and T is the tonnage of the products in the duration. The defined duration for 9-20 MVA furnaces is 7 days for a slag free process and 6 days for slaggy processes.

The energy for a start-up is consumed in electrode baking, warming-up charge materials and furnace lining, and forming the hearth structure. The heat loss is also included. For furnaces of a certain size, Wt should be approximate. Wh for each start-up, however, appears to be substantially different. This is mainly attributed to the different output during this period. Table 1 and Table 2 give some examples of the electricity consumption for both slag-free and slaggy processes in JFW. The figures show that the slag-free process requires some extra energy in the duration.

Table 1. Startup energy and production of some12.5 MVA FeSi75 furnaces

No. furnace	301	301	303	303	303	304	304	305
Time	1981.04	1975.06	1978.03	1981.05	1988.02	1988.02	1989.02	1977.04
Wt, MWh	1274	985	1384	1404	1358	1206	1372	1040
T. tonnes	90.5	0.0	94.9	89.9	109.5	115.0	109.0	0.0
Wh, MWh	478	985	549	613	395	274	413	104

Table 2. Startup energy and production of some 12.5 MCA HC FeCr and FeSiMn Furnaces

Product	HC FeCr				FeSiMn			
Furnace no.	102	102	102	102	101	101	101	102
Time	1975.03	1978.04	1983.02	1989.03	1975.02	1975.12	1986.12	1988.04
Wt. MWh	1022	970	778	1169	1023	944	793	936
T. tonnes	227.8	196.5	56.6	343.3	156.5	139.1	139.7	174.2
Wh. MWh	293	380	537	173	303	344	185	179

The procedure of a start-up usually consists of 3 steps:

(1) Electrode baking by burning coke cans or wooden logs. Simultaneously, the furnace lining is dried and preheated. In order to obtain sufficient length of electrodes, the holders should be moved to upper limit and be in a loose state.

(2) Electric warming-up.
At this stage, coke is charged in the furnace as electric and heat conducting media to warm the lining. Electrode baking is going on.

(3) Raw material charging.
When the temperature in the hearth becomes favourable for chemical reactions, the time is due for charging the burden. With increased load input metal and slag are accumulating under each electrode forming a smelting bath in the reaction zones or the so-called cavity structure.

A successful start-up has the following features:

1. Well baked electrodes without any breaks.
2. The chemicals of the products in the duration conform to the standards with least waste products.
3. Tapping operation and metal-slag separation are smoothly carried out on the scheduled time.

It is believed that electrode baking is the most important among the start-up operations, since frequent electrode failures cause a great deal of energy. Attention must also be paid to the charging rage and the tapping schedule.

In order to make a successful start-up, the development of a good start-up plan is of primary importance. It should include load input procedures, charging and tapping schedule, burden control programme and other operating parameters. For an existing furnace to be shut down, a detailed shutdown plan is also important, which is helpful to prevent electrode failure and to reduce economic losses.

MASS BALANCE AND HEAT BALANCE OF FURNACE START-UP

Mass balance and heat balance are helpful tools in the investigation of operation. The balances of a startup represents the accumulation of the materials and the energy input within the duration before the first tapping. Tables 3 and 4 list a typical balances for a 12.5 MVA FeSi75 furnace. All data are taken from the commercial operation. The are:

(1) 20 tonnes of coke was burned in coke baking and electric baking of the electrodes.
(2) 120 batches of burden were charged into the furnace before the first tapping. During this period the furnace consumed 0.18 million KWh of electric energy. Estimated 6 tonnes of hot metal was in the metal bath.
(3) Silicon loss during this stage is considerable. It is estimated from the gas volume and the dust content that approximately 30% of the silicon is lost in the form of dust.

Table 3. Mass balance of a 12.5 MVA FeSi75 furnace startup

INPUT		GAS OUTPUT		BURDEN MASS	
Term	Weight, tonnes	Term	Weight, tonnes	Term	Weight, tonnes
Quartz	36.0	Gas	143.5	Silica	17.6
Coke	19.2	Dust	3.5	Coke	3.7
Turnings	1.2			Iron Particles	0.5
Electrode paste	1.0			SiC	8.0
Coke for baking	20.0			Metal	6.0
Air	104.1			Slag	1.7
Scrap	3.0				
Total	184.5		147		37.5

Table 4. Startup energy balance of a 12.5 MVA FeSi75 furnace

INPUT			OUTPUT		
Term	Energy, BJ	%	Term	Energy, BJ	%
Electric	652.1	41.5	Metal Formation	55.2	3.5
Chemical	919.6	58.5	SiC Formation	122.1	7.8
			Electrode Baking	44.3	2.8
			Metal and Slag	16.7	1.1
			Lining Warming	100.3	6.4
			Burden Warming	100.3	6.4
			Furnace Gas	699.3	44.5
			Heat loss	433.5	27.5
Total	1571.7	100.0		1571.7	100.0

The ferrosilicon furnace hearth is characterized by its cavity structure, which mainly consists of silicon carbide and silica [3]. The formation of SiC consumes a great deal of energy. This is why the start-up of ferrosilicon furnace takes longer and uses more energy than the slag forming processes. During the first tapping, while the hearth temperature is relatively low and the charge is not full, the cavity around the electrodes is still rather small. The ratio of SiC and SiO2 (SiO_2) in it, however, should be stoichiometrical.

We may find some important information from the above balances:

(1) The heat efficiency during this period is very low. The yields of some elements is relatively low as well. The longer a start-up duration lasts, the more energy is lost. The way to improve the heat efficiency and the production results is to shorten these periods, especially to reduce the bared arc operation time.
(2) The energy used for baking the electrodes is considerable. In normal production the energy is 4180 kJ/kg [4,5,6]. The energy required for baking an electrode with a diameter of one meter is 1500-2000 kWh/m. The consumption during starting-up is even higher, since the heat efficiency is lower. Once an electrode failure occurs, not only the baking, but also the delay of start-up schedule consume much extra energy.
(3) Lining warming-up is a slow process.

Table 5 lists the temperature variation at the center part of the wall. It indicates that it takes one month to get a stable temperature gradient in the lining. The charging rate must be carefully controlled. Otherwise the freezing bath or "up-moving bottom" might occur, which is rather troublesome for tapping.

Table 5. Temperature variation of the lining during startup [3].

Day	1	2	3	4	9	12	18	28	36
Operation	Warming-up			Charging		Normal smelting			
T, °C	280	352	500	750	1130	1150	1230	1250	1280

(4) The metal produced from the reaction before the first tapping is too small to cover the hearth bottom. It is known that the metal bath plays an important role in warming up the lining and in maintaining the thermal stability of the hearth, since the presence of metal is favourable to heat transfer and to improve the operation. It is recommended that adequate addition of ferroalloy scraps should be included in the initial burden and the taphole level should be a little higher than the hearth bottom. The weight of the addition, however, should be less than the metal weight of a tap.

ELECTRODE OPERATION

Electrode operation is a serious problem during starting up. There are two ways to deal with the electrodes for an existing furnace.

(1) Directly energizing the furnace with the existing electrode tips.
(2) Starting-up with coke-baking electrodes.
(3) Starting-up with electric-baking electrodes.

The first one may reduce the energy cost and shorten the duration at this stage. The problem, of it, however, is the risk of electrode failures.

It is well known that during furnace shutdown thermal stress in electrodes may develop, which produces numbers of microcracks. During restart-up, the temperature gradient in electrodes makes the cracks growing and joining. Consequently, the strength is considerably reduced. The intensive vibration of the bare-arc operation during initial energizing is also harmful to the electrode strength. Once electrode breaks occur, a long stop deteriorates the performance of the other two electrodes. For the worse, a series of electrode failures may arise. As a result, the economy loss is serious. The high energy consumption of the starts-up listed in Tables 1 and 2 are all related to the electrode failures. The energy loss in these cases are much more than in normal electrode baking. Therefore, it is recommended to start a furnace with coke-baking electrodes.

During coke-baking, the electrode holders should be lifted to the upper limit to ensure a sufficient length to be bakes. The clamps should be kept loose to allow flame touching the electrode casing around the holders. Generally, it takes 48 hours and 15-20 tonnes of lumpy coke to bake three electrodes of 2.5 meters length and a diameter of one meter.

After coke baking, a carbon crust close to the steel casing is formed. Its electrical conductivity is not high enough to bear the full amperage. The strength of it, however, is enough to hold the total weight of the tip. Therefore, electric baking is still a necessity.

At 400°C, the self-baking electrode starts to react with oxygen in air. At 1000°C, intensive oxidation of carbon materials takes place. With low density and porous structure, a self-baking electrode is more sensitive to oxidation than graphite. In the hours of electric baking, the coke bed and raw material layer are thin and the extremely hot electrode tips, which are exposed to air, consume at a higher rate. If the duration of amperage increasing lasts too long, short electrodes may occur. Since the condition in the duration is not favourable to electrode baking, following with frequent slipping, soft breaks may occur. Therefore, the duration of amperage increasing must be in accordance with the length of the baked electrode. The following expression is proposed to calculate the duration before a full electrode current loading:

$$T_O < (L_b - L_n) / L_c \qquad \text{(hour)} \qquad (2)$$

where, T_o is the duration in hours, L_b is the length of coke baked electrode, L_n is the normal working length, L_c is normal slipping rate in cm/h. For example, the length of baked electrode is 250 cm for a 12.5 MVA, the working length is 150 cm, slipping rate is 2cm/h, then the calculated duration is 50 hours. It means that the time from energizing to full current loading should be equal to or less than 50 hours.

Mechanical strength of electrode is related to baking temperature and baking rate. It is known that a solid electrode may be obtained when the baking temperature is above 700°C (Table 6). A too high baking weakens the strength since the quick escape of volatiles from the paste produces a porous structure of the electrode just like a petroleum coke.

Table 6 Influence of baking temperature on electrode strength [4]

Baking temperature	°C	500	600	700
Electrode strength	MPa	30	43	53

In order to ensure the electrode strength, the load schedule must be carefully planned. It is considered that the load schedule may be divulged into three parts according to the electrode current. At the initial stage, the amperage may increase at a relatively high rate, since the baked part of electrodes is capable to bear certain amperage. A moderate rate of load increase is preferable as the amperage reaches up to 1/3 to 1/2 of the full current. Because the heat generation is proportional to the square of the current, the load rising rate in this period should be kept appropriate to correspond to the baking rate. When the baking is completed, the amperage may go up with a high rate. The load schedule for an open and a closed furnace respectively is shown in Figure 1.

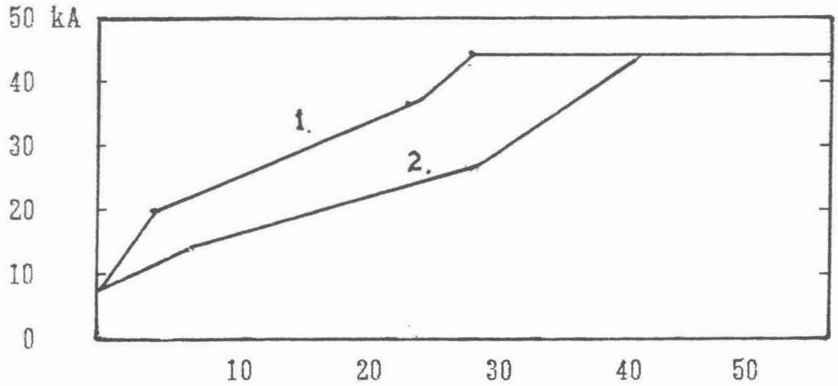

Figure 1. Typical load schedule for the start up of 12.5 MVA furnaces (1) for open furnace (2) for closed furnace.

For electrodes with a diameter less than 600 mm the temperature gradient is smaller and the thermal stress developed during cooling is less. The risk of electrode failure is much smaller. Therefore, it is possible to start up small furnaces with the existing electrode tips. In this case some measures must be taken to reduce the temperature gradient and the thermal stress and to prevent the formation of microcracks in the electrodes. Such as, before the furnace shutdown, the load should decrease slowly and after shutdown the furnace hood should be kept closed to reduce the cooling rate of the electrodes.

Most electrodes, working in air during start-up, are consumed quicker than during normal operation. As soon as the load is full it is the time to slip the electrode. Because the temperature in the hearth and in the electrode is still relatively low, the baking rate is low. The high resistance in the center part of the electrodes and the skin effects makes the current moving towards the surface. If the baking is abnormal and the slipping rate is too high, the steel casing will not bear the amperage. Thus, a soft break may occur in 5-20 minutes after the slipping. Therefore, the slipping rate must correspond to the consumed power of each electrode [5]. To be on the safe side, it is better to slip the electrodes frequently with small increment.

RAW MATERIALS CHARGING

The furnace hearth must have a rational heat distribution before the first tapping. It means that the bath temperature should be high enough to keep metal and slag superheated and the tapping channel unclogged. Early charging or a high charging rate may cause the hearth level to move upwards and make the tapping difficult. Delayed charging, however, may increase the heat loss and intensify electrode vibrations caused by the bare arc, which is very detrimental to electrode strength. A lesson was learned during a start up of a 25 MCA HC FeCr furnace, JFW in 1989, when the furnace had to be shut down as early as 96 hours after energizing due to hearth up-moving and clogging of the topping channel.

Usually charging starts at 1/3-1/2 of the full amperage, while the consumed energy is 1/5 of total power input for dry processes and 1/2 of total power for wet processes before the first tapping.

For normal operation, the charging rate should be in accordance with the power input of the transformer. The charging rate during start-up, however, should be higher. It is considered to be proportional to the power input. Therefore, it may be derived from the specific electricity consumption. Formula (3) is suggested for the calculation of charging rate, e.g. the charging batches in the duration of one MWh power input.

$$N = f * Co/(Q*Ce) \tag{3}$$

where, Co is the specific ore consumption in tonnes of ore per tonnes of the product, Ce is the specific power consumption in KWh/tonnes of the product, Q is the ore weight in one batch of charging and N is the number of charging batches in number/KWh. f is a correction factor. Some empirical f-values are listed in Table 7 as a reference. According to Eq. (3), the charging rate for a HC FeCr furnace during start-up is 8-10 batches in the duration of 10 MWh input.

Table 7. Empirical values of charging rate factor f.

Product	FeSi75	HC FeCr	FeSiMn
f	1.0 - 1.1	1.0 - 1.2	1.3 - 1.5

Careful charging, especially charging around the electrodes, must be taken to make the top of the burden moving up slowly. Because the charge layer is still thin, precaution should be taken to avoid moist materials or too much reduction material falling into the reaction zones.

It is well known that good permeability of the furnace burden is advantageous to the furnace operation. In order to improve the burden structure, it is suggested to charge some logs with proper size to the hearth before the initial charging of FeSi and CaSi furnaces.

FIRST TAPPING

It is well known from the heat balance that metal formation takes only a small part of the total heat input. Heat loss, however, is the major heat output. Some furnace troubles, especially the electrode breaks may aggravate the heat efficiency. Therefore, the power inputs before the first tapping for different performances varies greatly. When deciding the tapping time, all the factors which cause heat loss must be taken into consideration.

For furnaces making FeSi, CaSi, FeSiCr, a good start-up aims to form a proper structure of the smelting zone. The crust of the cavity wall mainly consists of intermediate compounds, metal droplets and some raw materials. Its formation requires a great deal of energy. As a result, the process requires more energy than slaggy processes and the time before the first tapping is longer.

The accumulated metal and slag bath has the advantage of warming the hearth. Early tapping may decrease the hearth temperature and promote the hearth moving-up. Delayed tapping, however, may make the metal level of the bath rise and force the electrodes up-moving.

Consequently, the heat loss increases and the furnace condition starts to deteriorate. Besides, the excessive metal is a risk in the ladle operation.

It is convenient to account the tapping time from the energy input. Formula (4) is given to estimate the power input before the first tapping.

$$W1 = k*Wn \tag{4}$$

where W1 is the power input before the first tapping, Wn is the normal power input of one tap and k is an empirical factor. Table 8 lists some data and some factor values arrived at for both slaggy and slag-free processes. They indicate that the energy required for different products of slaggy processes are approximate and the energy for a slag-free process is two to three times that for a slaggy process.

Table 8 Electricity consumption before the first tapping and empirical k values.

Furnace Capacity, MVA	1.0 - 1.8			9.0 - 12.5		
Products	HC FeCr	FeSi75	Si Metal	FeSi75	HC FeCr	FeSiMn
Energy before Charging MWh		8.0-15.0			40.0 - 50.0	
Energy before the first tapping, MWh	10.0	22.0	30.0	150.0	50.0	50.0
Energy for normal tap	3.2	6.0	6.0	21.0	22.0	22.0
k	3	3.6	5	5.7-7	2.2 - 2.3	

In order to keep the hearth temperature stable more power is usually needed also for the second and the third tap than for the normal tap. Therefore, the interval between the initial few tappings should be prolonged appropriately.

METAL CHEMISTRY CONTROL

The duration of a start-up usually lasts a few days. There are great differences between the initial and normal operation in the temperature distributions of the hearth, electrode tip positions, energy efficiencies and element yields. Unless certain precautions are taken big fluctuations in the product chemistry are inevitable.

In the first week of a newly started FeSi furnace, the layer of raw materials is still thin and the loss of silicon in the form of Si and SiO gas produced in the arc zone is considerable. Therefore, silicon yield is much lower than in normal production. On the other hand, the residence time of iron in the burden is much less than that of the silicon. Liquid iron particles easily penetrate the charge layer and fall into the metal bath. The silicon content may be decreased unless the weight of iron material in the charge is reduced. For a 12.5 MVA furnace the iron addition, mainly turnings, is usually 20-30% of the normal charge to ensure the product quality. If necessary, some iron-free charges are required.

Low temperature of the hearth is favourable to selective reduction. Some elements are easily reduced and some other are difficult. Iron, phosphor and sulfur reductions are preferential, whereas aluminium and calcium are difficult to reduce. Table 9 shows the phosphor variation of consecutive taps in several ferroalloys production during the initial period. Table 10 lists the variation of aluminium content in ferrosilicon of the first few taps. It is very common that the P and S content is higher and Al is lower than in normal taps. In order to ensure the chemical composition of the initial products, it is advised that raw materials with low phosphor content should be preferred for this stage.

Table 9. Phosphor contents in some metals of the first few taps (%)

Tap no.	1	2	3	4	5	6
FeSiCr	0.042	0.039	0.029			
FeSiCr	0.040	0.038	0.035	0.034		
FeSiMn	0.305	0.248	0.237	0.247	0.237	0.194
HC FeCr	0.062	0.049	0.043	0.049	0.047	

Table 10. Aluminium contents in FeSi75 of the first few taps (%) [6]

Tap no.	1	2	3	4
Furnace 303	0.39	0.51	0.69	1.08
Furnace 304	0.52	0.90	0.73	1.16

Attention must also be paid to the major element yields in the case of FeSi, FeSiCr and FeSiCa production, such as Si, Cr and Ca. Since iron oxide reduction predominates during starting-up, low contents of these major elements in the products may occur.

In fact, the variation of the product chemistry reflects the change of hearth temperature. It provides some information to judge the furnace operation and to adjust the charge proportion.

DIRECT START-UP

The cost of furnace start-up for some processes like FeSi, FeSiCa and Silicon metal is considerable. Not only the start-up consumes a great deal of energy and raw materials, but also it lasts a long time, while the furnace is often abnormal. From the economy point of view, it is rational to start up the furnace directly with the original hearth structure preserved, especially for plants where the furnace size is small and the power supply is variable in the year round.

The difficulty of this operation is:

(1) Poor electrical conductivity of the cold burden makes energizing and warming up difficult.
(2) Solidified charge is disadvantageous to gas permeability and heat transfer.
(3) The tapping hole is clogged.

The fact of short stops of the furnaces encourages the operators to consider the possibility of direct startup. It is noticed that after a 2-3 hours stop the charge is completely solidified. The permeability of the charge, however, may return to normal within hours when the furnace is reenergized.

To deal with the mentioned problems, the following operation is advised.

(1) Plan a detailed shutdown and start-up schedule. In order to protect the electrodes, carefully control the cooling and warming rate of the electrodes.
(2) Keep a tap of metal in the furnace. The metal bath is advantageous to electricity conduct and heat transfer. It is better to tune the production of FeSi75 to FeSi45 one or two taps before a shutdown. As soon as the furnace becomes normal the production may tune to FeSi75 again.
(3) Charge some turnings and coke before energizing the furnace.
(4) A higher voltage is preferable while initiating the arcs.
(5) Keep the tapping channel in a good manner.
(6) Control the charging rate. A high charging rate may cause the hearth up-moving and tapping trouble.

A successful direct start-up may save 50% of the cost. The practices [7,8] have shown that it is feasible for furnaces of small and intermediate sizes.

CONCLUSIONS

(1) The heat balance of furnace start-up periods indicates that the heat efficiency is very low. In order to improve the economy, it is suggested to shorten the duration.
(2) The electrode failure is costly. Care must be taken to deal with the warming rate of electrodes in order to reduce the effects of thermal shock.
(3) Some empirical formulas for furnace start-up are presented to evaluate the economy and to estimate the duration of warming up, the charging rate and the time of the first tapping.
(4) The chemistry of the products varies with hearth temperature. Adequate adjustments of the charge materials are required to ensure the product quality.
(5) It is feasible to start up the furnaces of small and intermediate size with the existing electrode tips and the smelting hearth structure preserved.

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