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Energy control in primary aluminium casthouse furnaces

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Abstract

Controlling and reducing the energy consumption in aluminium melting/casting furnaces are key factors influencing the casthouse economy and the carbon foot-print. In order to effectively run a furnace with low energy consumption the burner's fuel consumption in the different charge stages needs to be monitored. Furthermore, the furnace and burner need to be sufficiently instrumented to continuously measure important furnace parameters and relate these to the resulting melt temperature, and hence the energy consumption.

The paper gives operational experience of reducing the melting/casting furnace energy consumption in a Hydro Aluminium primary casthouse.

Introduction

The furnace energy consumption in primary casthouses is governed by physical factors like furnace lining type and condition, burner type and maintenance, off-gas stack condition, furnace pressure, cold metal type and share, and pot-room metal temperature.

In addition, operational parameters are also very important in order to control the furnace energy consumption. These are related to controlling the amount of energy added to the cold metal before pot-room metal is added, timing of furnace operations and hitting the correct metal temperature before start casting.

A complete primary furnace cycle (one-furnace practice) consists of charging cold metal, including alloying elements, to the furnace, pre-heating the cold-metal, adding pot-room metal, stirring, skimming, adjustment of elements including melt homogenising, sampling, temperature adjustment and finally casting. Depending on the cold metal share, the main part of the energy added via burners goes to heating the cold metal so that the final furnace melt temperature before casting reaches a predefined level.

The main part of the energy consumption in a primary casthouse furnace is linked to the preheating of cold metal before adding pot-room metal to the furnace.

In this paper the focus will be directed towards operational experience with energy reduction in a Hydro Aluminium primary casthouse producing foundry alloys.

Furnace stages and energy addition

The cycle of the Hydro Aluminium primary casthouse furnace consists of the following operations or activities per charge:

1. Scraping (cleaning) refractory after previous charge.
2. Charging of cold metal.
3. Preheating of cold metal.
4. Charging of pot-room metal.
5. Stirring, skimming and alloying.
6. Sampling, analysis and chemical adjustment.
7. Temperature adjustment.
8. Casting.

The energy data presented in this paper comes from a Hydro Aluminium foundry alloy casthouse, where the total energy added to each charge from the furnace burners is divided into three stages or sub-processes:

$$\text{Total energy consumption per charge} = \text{Burner energy to (Cold metal preheating + Alloying + Casting)} \quad (1)$$

Normally, the main part of the burner energy goes to cold metal preheating. This, however, depends strongly on the cold metal share, so if the cold metal share is less than approximately 10 %, the burner energy addition in the preheating stage is small compared to the casting stage.

In this paper only energy data from charges with relatively high cold metal share is presented, i.e. generally between 25 and 40 %.

The energy addition in the alloying stage should be small possible, preferably zero, since the heat transfer rate to liquid aluminium from the burners is slow compared to solid aluminium, resulting in a relatively high heat loss. During casting energy is added to maintain the melt at the correct casting temperature. If the casting duration is several hours, as it can be for foundry alloys, the energy consumption during casting can be considerable, and represent up to one third of the total charge energy consumption.

In order to be able to improve on energy consumption it is essential to measure energy consumption on charge basis. However, this is not sufficient in order to find the root cause of excessive energy consumption, so each charge must be split into stages, or sub-processes, according to Equation (1), and the energy consumption in each sub-process should be analysed to find reasons for deviations from the normal or ideal energy consumption.

The energy consumption in the preheating part is to be compared to a calculated (theoretical) energy amount, based on material data like heat capacities and latent heat of fusion, including an empirical furnace heat loss, to obtain a planned energy need for cold metal preheating to reach a target temperature on the melt before casting.

Cold metal energy calculator

In order to run the furnace process optimally it is crucial to be able to add sufficient energy to the cold metal before the liquid metal is added to the furnace. At the same time it is also important not to add too much or too little energy to the cold metal. Both will lead to increased energy loss since in the first case the necessary energy has to be added to the liquid bath with much lower heat transfer ability than cold metal. In the latter case the excessive heat must be released from the melt by opening doors, hatches, etc. This is obviously a waste of energy and time.

The theoretical energy (in the unit kJ or alternatively in the unit kWh in this paper) for a charge with a specified weight needed to reach, say 720 °C, in melt casting temperature, could be calculated using equation 2 (excluding heat loss):

$$E_{Theor.} = E_{Al, 20-660°C} + E_{Al, latent\ heat} + E_{Al, 660-720°C} + E_{Si, 20-720°C} - E_{Pot\text{-}room} \quad (2)$$

where $E_{Al,\ 20\text{-}660°C}$ is the energy needed to bring a specified weight of aluminium from 20 °C to 660 °C, $E_{Al,\ latent\ heat}$ is the latent heat of melting a specified weight of aluminium, $E_{Al,\ 660\text{-}720°C}$ is the energy needed to bring a specified weight of aluminium from 660 °C to the target temperature of 720 °C, $E_{Si,\ 20\text{-}660°C}$ is the energy needed to bring silicon from 20 °C to 720 °C including dissolving silicon in aluminium and the mixing energy of aluminium and silicon, and $E_{Pot\text{-}room}$ is the energy gained from bringing pot-room aluminium from 850 °C down to the target temperature of 720 °C.

Including heat loss, the actual energy need from the burners is then:

$$E_{Actual} = E_{Theor.} \times 1.3 \quad (3)$$

The factor 1.3 is an empirical factor that is specific for each furnace and burner system, and can be interpreted as a heat loss for the total furnace combustion system.

Optimal furnace energy consumption

In order to reduce energy consumption in a primary aluminium casthouse there has to be a strategy on how to run the burners and when to add energy to the charge.

Looking at the furnace activities or operations during a furnace cycle, the distribution of energy addition from furnace burners can be split (strongly depending on cold metal share, though) as shown in Figure 1.

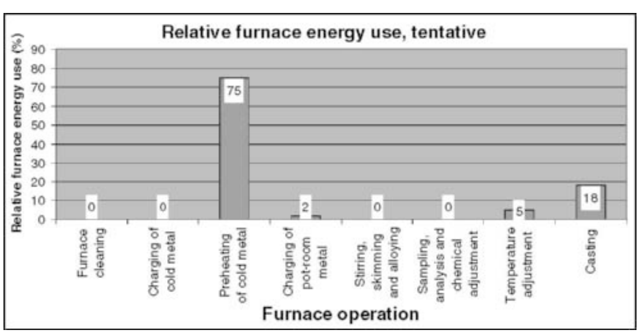

Figure 1. Relative energy use per furnace operation with cold metal share of around 40 %, first version.

As can be seen, the energy use in some of the operations is (close to) zero. As indicated earlier, the energy in the pre-heating stage is the main input to the charge. Depending on the casting time duration, there needs to be some energy input in the casting stage to compensate for the heat loss during casting and maintain the melt temperature out of the furnace constant.

With respect to energy the furnace cycle was split into the three sub-processes, here denoted "Cold metal pre-heating", "Alloying" and "Casting", see Figure 2, covering a complete furnace charge cycle.

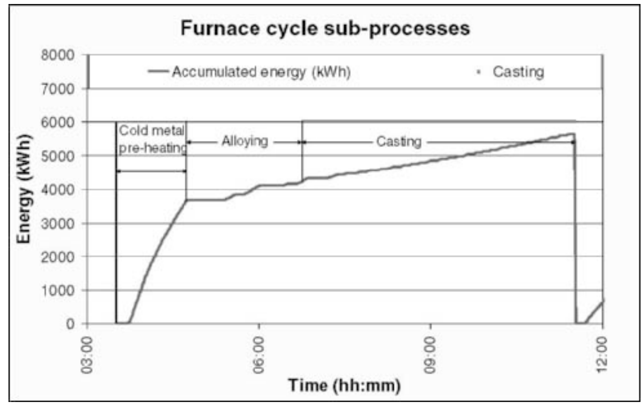

Figure 2. Definition of furnace cycle sub-processes with respect to energy consumption; "Cold metal pre-heating", "Alloying" and "Casting". The blue line shows the typical accumulated energy in the three sub-processes.

The definition of the three sub-processes is:

1. "Cold metal pre-heating": Time from furnace down from previous cast until start pot-room filling into furnace, i.e. including furnace cleaning, cold metal charging and cold-metal pre-heating.
2. "Alloying": Time from first pot-room filling until start casting, i.e. charging pot-room metal, stirring, skimming, alloying, sampling, analysis, chemical and temperature adjustment.
3. "Casting": Time from start casting to end casting.

Modifying the tentative furnace energy use in Figure 1 according to these three sub-processes, gives an "ideal" relative energy use for a cold metal share of around 40 %, see Figure 3.

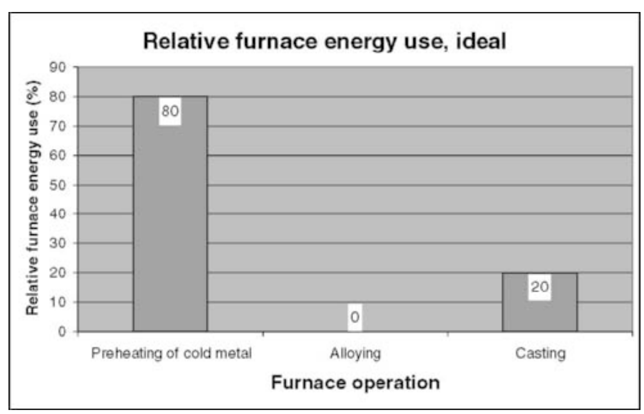

Figure 3. "Ideal" relative energy use per furnace operation per charge for a cold metal share of around 40 %.

Note that in Figure 2 there is some energy use in the “Alloying” stage, which is not the ideal situation.

Looking at a typical temperature development in a charge from start cold metal pre-heating until start casting, Figure 4, the temperature increase in the cold metal comes from burner activity (sub-process “Cold metal pre-heating”), whereas in the “Alloying” stage the temperature increase comes from the hot pot-room metal addition with little or no burner activity.

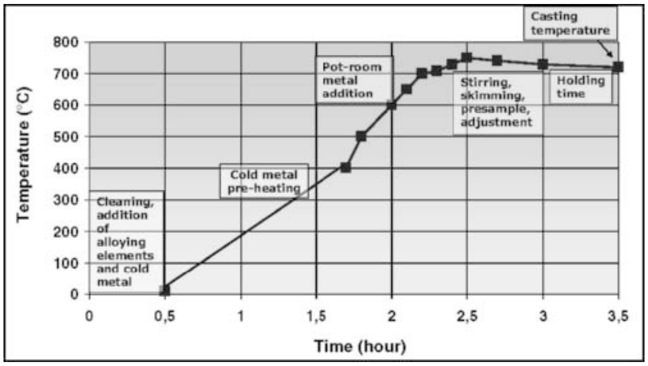

Figure 4. Typical furnace average charge temperature development from start cold metal pre-heating through to start casting.

The key parameters that were/could be used to reduce furnace charge energy consumption are burner effect, the energy added to the furnace (accumulated), the resulting metal temperature in a typical charge during a complete furnace cycle and the furnace pressure. The parameters are plotted in Figure 5 as a function of time together with indication of planned energy to be added to the cold metal before addition of pot-room metal, i.e. 3182 kWh, and timing of the addition of the pot-room metal.

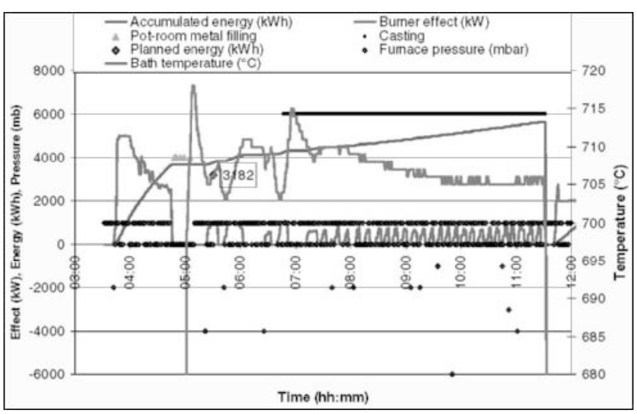

Figure 5. Burner effect (kW), accumulated energy (kWh), furnace pressure (millibar), first y-axis, and melt temperature (2nd y-axis) during a typical furnace cycle. Also indicated is planned energy for pre-heating the cold metal (3182 kWh) and time when the pot-room metal was added.

To further understand the energy consumption in the different sub-processes, the “Cold metal pre-heating” stage in Figure 5 was further broken down. This is expanded in **Figure 6**. The burner effect is constant in the first part of the cold metal pre-heating, gradually decreases, and then drops to zero. The reason for the decrease is that the burner effect was regulated by the off-gas and roof temperatures (not shown in the figure). When these reach their limits, the burner effect is reduced accordingly. The last drop to zero is due to the fact that the burners are not running during pot-room metal filling.

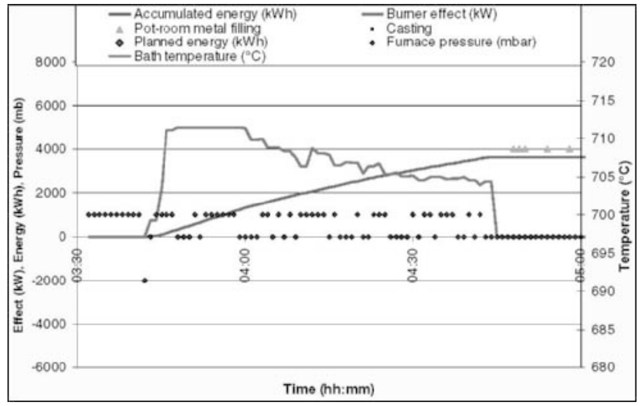

Figure 6. Burner effect (kW), accumulated energy (kWh) and furnace pressure (millibar) during the “Cold metal pre-heating” stage from Figure 5.

The accumulated energy value when the first pot-room metal is supplied, i.e. the flat part of the blue line in **Figure 6**, is important for the correct development of the temperature in the rest of the charge cycle.

This latter situation is shown in Figure 7 from the “Alloying” stage in Figure 5 where there is some burner activity. Note the planned energy value 3182 kWh from the cold metal energy calculator. This value should be compared to the flat part of the blue line in **Figure 6**, i.e. 3666 kWh, and the difference will be plotted for several consecutive charges.

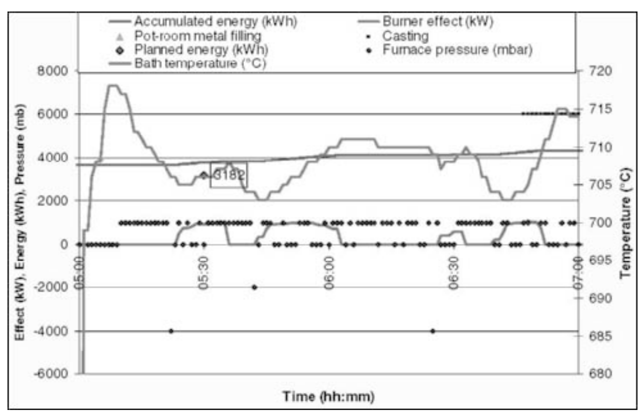

Figure 7. Burner effect (kW), accumulated energy (kWh), furnace pressure (millibar) and melt temperature during the “Alloying” stage from Figure 5.

In the last furnace cycle stage, “Casting”, the burner activity was kept low and was controlled by the melt temperature in the launder during casting, **Figure 8**. Note the mainly positive value of the furnace pressure during the casting part even if the burner effect is low. This is due to the fact that the furnace is equipped with a baffle in the stack that regulates the off-gas in such a way that a positive furnace pressure is maintained in the furnace at all times.

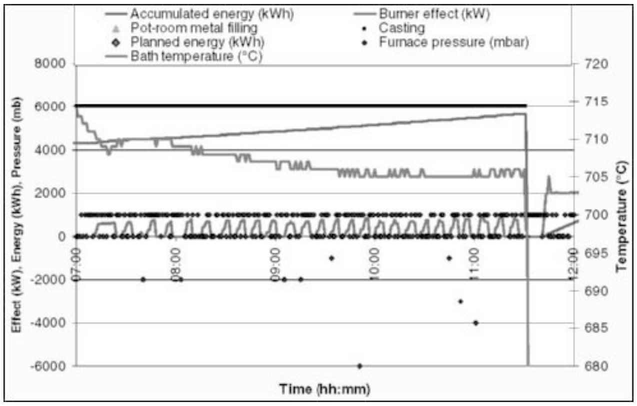

Figure 8. Burner effect (kW), accumulated energy (kWh), furnace pressure (millibar) and melt temperature during the "Casting" stage from Figure 5.

Returning to the total furnace cycle in Figure 5, the difference between the actual used energy for cold metal pre-heating and the planned energy calculated from Equation 3 is illustrated in Figure 9.

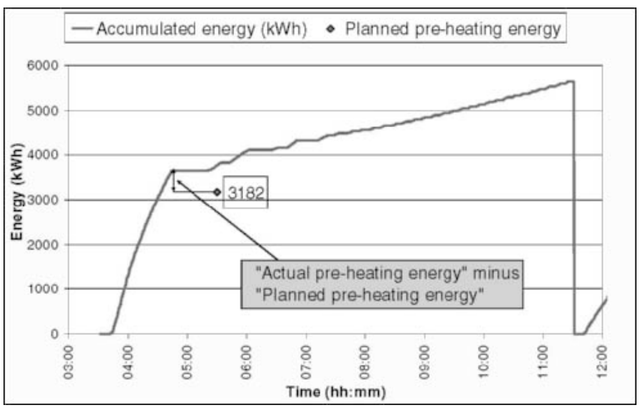

Figure 9. Illustration on how to calculate the "actual cold metal pre-heating energy" minus "planned pre-heating energy" from Figure 5.

By plotting this difference for consecutive charges on one furnace, an SPC-plot was constructed, as seen in Figure 10. In the same plot, upper and lower control limits, UCL and LCL, are also included. The goal is to reach a difference of zero between the actual and the planned pre-heating energy.

From Figure 10 the average difference between the actual pre-heating and the planned energies is around 500 kWh per charge. This means that each charge in average receives 500 kWh too much in the pre-heating stage. This excessive heat will probably need to be released from the charge by opening the furnace door to cool down the charge, i.e. the excessive energy applied will be wasted.

So the goal in Figure 10 is to reach zero in average value. But this is not enough; also the variation from charge to charge needs to be strongly reduced in order to reduce the overall energy consumption. All charges that are above the upper control limit and below the lower control limit must be analysed with respect to energy consumption after it is finalised in the furnace, i.e. to look for the reason for excessive high or low (negative) energy differences.

One reason can be that the pot-room metal is filled too early or too late to the furnace, resulting in too little or too much pre-heating energy to the cold metal.

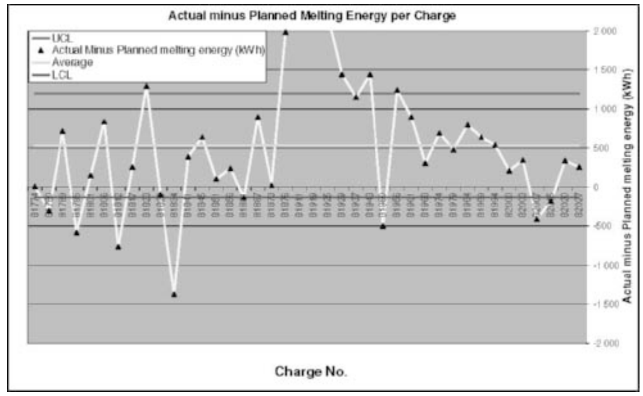

Figure 10. SPC-plot of actual pre-heating energy minus planned (calculated) energy per charge.

Another way of closely following the energy consumption is to plot the temperature after skimming, see Figure 11. This temperature will reveal if the cold-metal pre-heating energy is applied correctly. From Figure 11 this temperature varies quite a lot, typically from 705 to 755 °C, underlining the rather big variation in the "actual" minus "planned" cold metal pre-heating energy per charge. It is expected that the variation in temperature after skimming from charge to charge is greatly reduced if the variation in the "actual" minus "planned" cold metal pre-heating energy per charge is reduced.

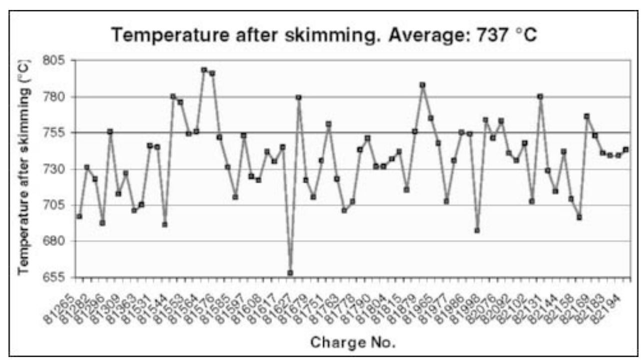

Figure 11. Temperature measured in the furnace melt after skimming.

Furthermore, the temperature after skimming can be used to modify the calculation of the planned pre-heating energy in Equation 3, basically by changing the empirical factor, i.e. 1.3, so that the calculation of the planned energy fits the actual energy used when the temperature after skimming reaches its target. However, this requires that the furnace melt temperature after skimming is homogeneous.

Furnace equipment necessary to control energy consumption

In order to control the energy consumption in a primary casthouse with a considerable cold metal usage, there are several parameters that need to be measured, and furnace equipment that needs to be installed. Similar work has been done earlier to identify furnace heat losses [1] and improve furnace productivity [2].

First of all, roof and off-gas temperatures need to be used to control the effect of the burner. Both of these are important in order to correctly run the burner. When either of these reaches its maximum limit the cold metal is no longer able to absorb the energy at the same rate as earlier, i.e. when the cold metal gets heated the heat absorption is reduced. If the maximum burner effect is high enough, gradually more of the burner energy is going to the furnace lining and eventually to the off-gas. Therefore the burner effect needs to be reduced during pre-heating to avoid energy being wasted through the off-gas.

Secondly, there need to be suitable baffles installed in the off-gas system to regulate the furnace pressure during all stages of the furnace cycle so that the furnace pressure is always slightly positive, i.e. with a small over-pressure in the furnace to avoid suction of false air through furnace openings like doors, hatches, etc. This is especially important when the burner is running on low effect, since this produces less off-gas from the burners and hence less over-pressure from the burner.
Moreover, measurement of the furnace pressure to improve process operation and pressure control and hence avoid suction of false air during all burner effect settings should be performed.
Linked to furnace pressure is also the importance of keeping furnace doors and openings as tight as possible when they are closed in order to avoid false air suction into the furnace.

Thirdly, furnace metal temperature must be measured continuously during the furnace cycle as soon as there is liquid metal in the furnace. As indicated earlier in this paper, the metal temperature is a good indicator that the correct pre-heating energy has been added to the cold-metal.

In order to verify burner settings, in-line off-gas analysis should be installed to measure the O_2-content. An optimal O_2-content in the off-gas is around 2 %. Higher O_2-content than this would indicate that there is a suction of false air into the furnace.

Finally, there needs to be adequate data acquisition of critical furnace parameters. These need to be followed up on charge basis, e.g. with SPC-plots, in order to give a timely and correct response to the way the furnace operations are performed.

Conclusions

Based on a comprehensive analysis of furnace energy data in a primary Hydro Aluminium casthouse the following conclusions can be made to reduce furnace energy consumption:

1. Split the furnace cycle into sub-processes and follow-up the energy consumption in these sub-processes on charge basis with SPC-plots.
2. Apply the correct, planned or calculated, energy from the burner to pre-heating the cold metal before pot-room metal is filled to the furnace.
3. Avoid burner activity to liquid metal except during casting.
4. Ensure that the burner effect is reduced according to maximum limits on off-gas and roof temperatures.
5. Ensure that there is a small over-pressure in the furnace when doors are closed in order to reduce false air suction.
6. Measure furnace melt temperature during the complete cycle and use this to calibrate the calculated pre-heating energy.

References

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2. P. Whiteley: “Means of improving casthouse productivity”, *Light Metals 2010*, Ed. John A. Johnson, TMS 2012, 723-727.