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CAST SHOP FOR ALUMINUM PRODUCTION

Furnaces and Energy Efficiency

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DEVELOPING A DO-IT-YOURSELF EXCEL MODEL OF A REVERBERATORY SIDE-WELL ALUMINUM MELTING FURNACE

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Abstract

There is great incentive for improving the energy efficiency of aluminum melting and holding furnaces. Many factors affect the amount of energy required to melt scrap aluminum, but the influence of each factor can be difficult to quantify. The effect of each factor on the flow of material and energy can be calculated by developing a system model of the process. The most effective model utilizes the fundamental laws of mass and energy conservation, along with empirical relationships developed from plant observations. This paper describes the procedure for developing an Excel model for a 113,000 kg (250,000 lb) side well furnace melting 120.5 kg/min (7200 kg/hr, 15,900 lb/hr) [1]. Simulations were carried out with the aid of specially-developed Excel add-in programs. The results were used to optimize the firing rate for minimizing the specific energy requirement, and quantifying the use of special energy-saving techniques.

Introduction

Energy is a significant portion of the manufacturing costs for recycling aluminum scrap. While natural gas prices have come down lately, no one can foresee the future, especially regulation costs for reduction of greenhouse gases. Increased thermal efficiency in the remelt process is therefore a continuing challenge to plant operators seeking cost savings.

Meeting this challenge requires improving the melting process and the combustion system through the use of techniques for reducing the fuel energy required to melt scrap, and maximizing the recovery of ingot from scrap. Some of the best-practice techniques involve:

- Air-fuel ratio control
- Preheated scrap
- Preheated combustion air
- Bath stirring
- Improved furnace insulation and maintenance
- Oxidation-loss reduction
- Furnace pressure controls
- Improved heat transfer in the furnace
- Optimized melt rate

Clearly, finding the right mix of operating factors to maximize thermal efficiency is not easy. Success requires analysis of the intricate combustion and heat transfer processes inside the furnace. This task can be made easier through the development of a mathematical model of the process. By performing a series of computational studies, a broad range of furnace parameters can be simultaneously studied and the overall effects of these changes plotted against one another, yielding a consistent means of optimizing furnace operation under prescribed conditions. With a comprehensive "map" of furnace performance, less guesswork is required in conducting actual furnace experiments.

Techniques for developing and using process models has advanced greatly over the past two decades, mainly owing to advances in computer software and machine capability [2, 3]. A model is essentially a collection of mathematical equations that define relationships between independent and dependent variables in a system. Insofar as possible, model equations should be based on the fundamental laws of conservation of mass and energy, the laws of thermodynamics, fluid flow, heat transfer, and chemical kinetics. Process models may also contain equations that relate transient conditions and other practical constraints [4, 5].

Different objectives require different models and computational techniques. Sometimes a very simple model can contribute to the understanding of a portion of a process, while a very elaborate model may be required to simulate a plant. Commercial software [6 – 8] is readily available for those applications. The purpose of this paper is to outline a technique for developing a do-it-yourself Excel-based steady-state model for the melting of scrap aluminum in a sidewall reverberatory melting furnace of defined size. Such a model has built-in limitations [9], but may be quite adequate for many applications or at least as a good starting point before embarking on the development of a more sophisticated model. The Excel-based procedure outlined in this paper is applicable to building a model for almost any chemical process.

The Side-Well Reverberatory Melting Furnace

Aluminum side-well melting furnaces are essentially large heat exchangers. Heat is provided by combustion of a fuel (usually natural gas) in a combustion chamber, and is transferred from the products of combustion (POC) in the gas blanket to the contents of the furnace. The melt rate is a balance between the heat-releasing medium (the POC) and the heat absorbing medium (mainly aluminum, plus the furnace containment structure). Heat is transferred mainly by radiation to the walls and bath, but the model does not deal with re-radiated heat. It only accounts for net heat transfer. Figure 1 shows a typical sidewell reverberatory aluminum melting furnace [4].

Scrap and flux are added to the well and pushed into the main batch where much of the melting occurs. The melting scrap flows under a weir, leaving behind the dross and flux. These furnaces produce a clean bath with less dross and are capable of lengthy periods of continuous operation. A stack melter is another variant of the traditional reverb melter. The furnace flue gases exit the furnace through a scrap charging area, which preheats the scrap. These furnaces have a higher thermal efficiency than conventional reverb furnaces.

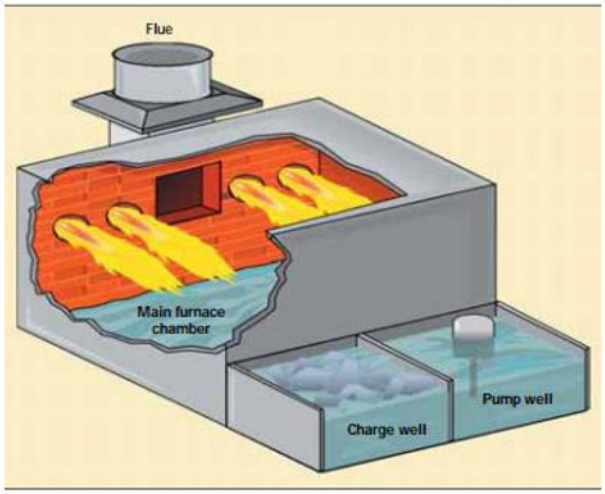

Figure 1. Basic sidewell reverberatory melting furnace. During charging, molten aluminum is pumped through the charge well, where it melts scrap and then circulates back into the main furnace chamber for reheating [4].

The speed of metal circulation and the metal bath temperature dictate the charging rate. The desired average metal temperature at the inlet to the pump weir is 730 °C to 760 °C (1350 °F to 1400 °F). The melt temperature decreases in the charging well and increases in the bath. The rate of energy delivered to the charging well is directly linked to the melt temperature, its circulation rate, and heat transfer rate from the POC to the bath.

Molten aluminum oxidizes to form dross when exposed to furnace gases. The dross formation rate is determined by oxygen availability at the melt surface and the melt temperature. Excess dross is highly undesirable because it represents a potential loss of aluminum, and hinders heat transfer from the POC to the underlying metal. These two important parameters require attention in maximizing the recovery of metal from scrap [10].

Model Description

Process simulation was carried out in three stages. First, a basis-case model was developed to examine changes in thermal efficiency caused by variations in percent excess air, stack gas temperature, leak air flow, heat loss, dross make, etc. Second, the basis-case model was enhanced to include provisions for preheating the combustion air or scrap. Third, the model was used to make simulations to quantify the effect of input changes on system variables relating to energy consumption [1].

Every model contains four types of information. First are *specifications* that you, as the model builder, will choose to fix as constant. Some examples are system pressure, a stream composition, or the heat loss. Second is *data*, such as the atomic mass of the elements, the vapor pressure of water, or the heat of formation of a compound. Third are *independent variables*, which you plan to change in making simulations. Fourth are *dependent variables*, which derive their value from the model equations that relate all four of the information types. The model is structured for forward calculation, in which the independent variables are chosen primarily from instream properties.

Model Specifications

The specific furnace selected for this analysis was a typical large reverb furnace, with a nominal holding capacity of 113,400 kg (250,000 lb), 55 m^2 (580 ft^2) surface area, and 0.76 m (30 in) bath depth. The scrap was assumed be pure aluminum, and no account was taken for combustion of scrap organics. Figure 2 shows a sketch of the process flowsheet. Operation is steady-state, with one minute of operation chosen as a basis.

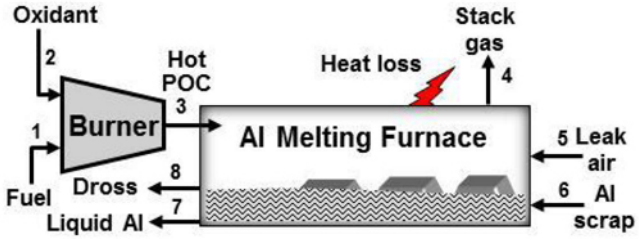

Figure 2. Flowsheet sketch of basis-case process model. For heat balance purposes, the burner is considered an integral part of the furnace.

Data

The thermophysical and thermochemical data required for the model was obtained from the FREED thermodynamic database program [11]. The first type of required data are heat contents of the substances involved in the process: ten species in the natural gas fuel (two of which are common to other streams), four POC species, air, aluminum, and aluminum oxide (Al_2O_3). For modelling purposes, heat contents were required in equation form. This was accomplished by charting tabular data, and using Excel's Trendline tool to obtain linear or quadratic expressions to fit the data. Figure 3 shows the results of this procedure for aluminum. For model use, the Trendline equation units for aluminum were converted to units of kJ/kg. For gases, two equation sets were required; one for moderate temperatures (25 °C to 1350 °C), and one for high temperatures (1300 °C to 2650 °C).

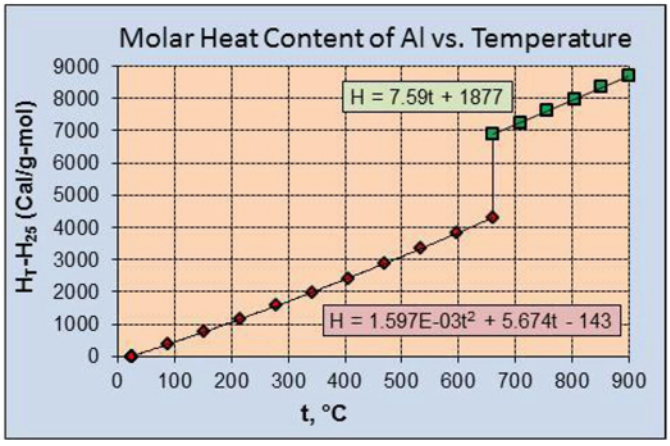

Figure 3. Molar heat content of aluminum as a function of temperature. Text boxes produced by Trendline tool. A quadratic equation gives a satisfactory fit for the solid phase, while a linear equation is satisfactory for the liquid phase. The discontinuity at 660 °C represents the heat of fusion of aluminum at its melting point.

The second type of data required from FREED is that for the heat of formation of substances at 25 °C. This data is used, in turn, to calculate heats of reaction at 25 °C; especially the heat of combustion of the fuel gas and the heat of oxidation of aluminum to form Al_2O_3. Finally, data is required for the equilibrium constant for certain chemical reactions taking place in the POC, such as the formation of NOx.

The heat balance for a system involves setting the sum of all heat effects to zero. The heat of combustion of a hydrocarbon is of particular interest here, since water is one of the components of the POC. If $H_2O(liq)$ is used as the standard state of water at 25 °C, the resulting combustion heat is designated the *high heat value* (HHV), while if $H_2O(gas)$ is used as the standard state, the result is the *low heat value* (LHV). The model adopts the LHV for heat balances, with a conversion factor for those wishing to use the HHV [12, 13].

Independent Variables

There are 24 input process variables, of which ten are the fuel gas composition. Each one of the 24 input variables is independently adjustable. The model calculates the flow, composition, and temperature of each stream and the distribution of energy between different outstreams. These results allow calculation of an *absolute* and a *specific* energy requirement in two forms: combustion heat and total heat. The latter term includes heat entering as sensible heat in the instreams. The specific energy requirement is the absolute value divided by the mass of aluminum recovered. Independent variable values selected for the initial basis-case model are:

1. 14.5 m^3/min (512 cfm) natural gas firing rate)
2. 80,000 kJ/min (76,000 Btu/min) heat loss
3. 1170 °C (2140 °F) POC stack gas temperature
4. 770 °C (1420 °F) aluminum bath temperature
5. 20.57 $\%O_2$ in humid air oxidant at 6 % excess*
6. 7 m^3/min (250 cfm) leak air rate
7. 3 kg/min (6.6 lb/min) dross containing 55 % metallic Al
8. 96 $\%O_2$ in the industrial oxygen, but no oxygen enrichment.
9. 25 °C (77 °F) entering temperature for all instreams.

Extended Basis-Case Model

The main purpose of the basis-case model is carry out process simulations that will show process trends when any one of the first eight variables is varied over a range of values. Extensions were added to the basis case model to examine the effect of variations in the ninth variable. First, preheating the combustion air by extracting heat from the stack gas (stream #4 in Figure 3). Second, preheating the scrap by extracting heat from the stack gas (i.e., using a stack gas melter). Both of these techniques are in common use.

Combustion Air Preheating

A furnace's stack gas often contains more heat than does the product being heated. Process engineers have long recognized thermal efficiency could be improved by capturing much of the stack gas heat and returning it to furnace as preheated oxidant. Every kJ of heat transferred to the oxidant is one less kJ that must be supplied by fuel combustion. Combustion air heating can be accomplished by using a recuperator or a regenerator. A recuperator operates continuously by means of a heat exchanger installed in the furnace stack; while a regenerator alternates the combustion air and stack gas between heat storage devices. To quantify the potential energy savings, a stack gas recuperator device was added to the flowsheet, as shown in Figure 4. The HX device employs a splitter for the combustion air to allow for a range of heat transfer efficiencies from stack gas to air. None, some, or all of the burner oxidant passes through the HX. If none of it passes through the HX, it is not preheated, so it enters the burner at the ambient temperature. Oxidant passing through the HX enters the burner at a user-defined temperature. A heat and material balance around the HX quantifies the relationship between the preheated oxidant temperature and the HX bypass flow.

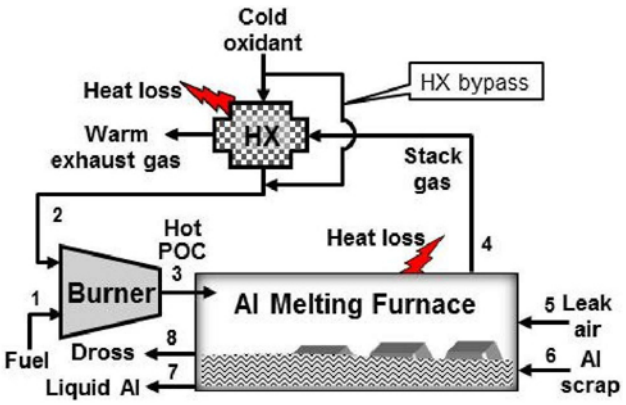

Figure 4. Process flowsheet with an oxidant recuperator added to the basis-case model. The model employs an oxidant bypass to vary the amount of heat transferred to the oxidant.

Scrap Preheating

Another way to save energy is to pass the stack gas through a stack containing the scrap, as shown by Figure 5. Some side-well furnaces have this ability built in, while others may require a retrofit. The heat transfer efficiency to the scrap may not be as effective as that for heating the air.

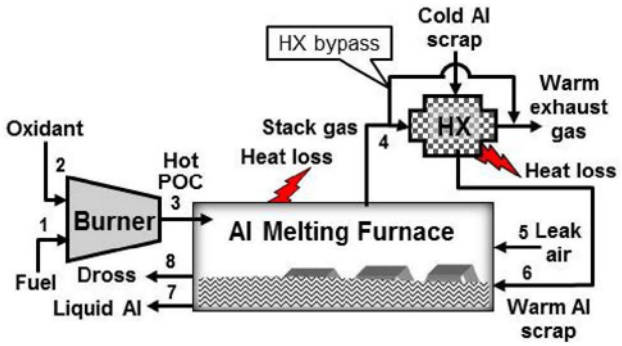

Figure 5. Process flowsheet with a scrap recuperator added to the basis-case model. The model employs a stack gas bypass to vary the amount of heat transferred to the scrap.

* Air oxidant enters at a dew point temperature of 18 °C. Normal dry air contains 21 $\%O_2$.

The Structure and Operation of the Basis-Case Model

The general strategy in developing a process model is to structure it so that a material and a heat balance can be made around each device. Simple processes often allow both types of balances to be made separately; i.e., the material and heat balance around a device are *uncoupled*. But in more complex cases, the two balances are *coupled*, which means that both balances must be made together. The balances around the burner are uncoupled, while those around the furnace are coupled.

Burner Model (Uncoupled)

Worksheet cells contain material balance formulae that operate on the gas instreams (streams 1, 2, and 3). Basis units of volume or mass are converted to molar amounts for all calculations. Table I shows the fuel composition for the basis case. The first task is to calculate the amount of each POC from chemical reactions of the fuel gas species. Equations [1 - 3] show generic combustion reactions [12] for hydrocarbon species, CO, and H_2:

$$C_xH_y + (x + \tfrac{1}{4}y)O_2 \rightarrow xCO_2 + (\tfrac{1}{2}y)H_2O \quad [1]$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2 \quad [2]$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \quad [3]$$

The basis-case fuel flow is 0.5927 kg-mol/min, and the molar oxidant-fuel ratio for the basis-case fuel gas burned with the stoichiometric amount of humid air is 9.9596. The actual fuel air ratio at 6 % excess oxidant is then 10.56. A material balance [14] around the burner gives the composition of stream 3 as 9.1 %CO_2, 19.3 %H_2O, 1.1 %O_2, balance N_2.

Table I. Fuel Composition for the Basis Case Model (Percent by Volume)

CH_4	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
93.00%	0.04%	3.00%	1.00%	0.50%

H_2	CO	CO_2	H_2O	N_2
0.00%	0.00%	1.50%	0.00%	2.46%

A heat balance around the burner is used to solve for the one remaining unknown variable: the temperature of burner stream 3. Since the burner has no heat loss, this will be then adiabatic flame temperature (AFT). The heat of combustion of each reactive component of the fuel gas is calculated from tabulated thermodynamic data, and summed to give an LHV of 487,900 kJ/min (462,900 Btu/min). This value was set equal to the sum of heat contents of the stream 3 species, with temperature as an unknown. The resulting quadratic equation was solved to give an AFT of the hot combustion gas of 1932 °C (3510 °F).

Furnace Model (Coupled)

The material balance around the furnace starts with an oxygen balance. The leak air contributes 0.0601 kg-mol/min of O_2 and 0.2260 kg-mol of N_2 to the combustion gas stream, while the oxidation of aluminum to form 3.0 kg of dross consumes 0.636 kg-mol of O_2. However, the mass of Al melted/recovered is a dependent variable, which causes the oxygen and aluminum material balance around the furnace to be coupled to the heat balance around the furnace. This requires a combined heat *and* mass balance equation that contains the mass of aluminum exiting the furnace and its heat content [15]. The result showed that 121 kg/min scrap enters the furnace, and 118 leave as molten bath [1].

Implications of the Basis-Case Model Results

The model tabulates certain specific energy factors involved in the process. Table II shows the specific energy consumption required to melt aluminum when operating the melting furnace at the basis-case conditions. Recall that 487,900 kJ/min (462,900 Btu/min) were generated by the combustion of 14.5 m^3/min (512 cfm) of natural gas. To this, 22,000 kJ/min (21,000 Btu/min) of heat are contributed by dross formation.

Table II. Specific Energy Consumption for the Basis-Case Model for Scrap Melting.

	Fuel only	Fuel + dross
kJ/kg	4129	4317
Btu/lb	1776	1857
kWh/tonne	1147	1199

The values in Table II are large compared to the minimum theoretical energy required to melt aluminum and bring it to the basis-case tapping temperature of 770 °C. Figure 3 indicates this value as 7720 cal/mol, or 1200 kJ/kg (500 Btu/lb). So the basis case melting process uses about 3.6 times as much heat as the theoretical minimum. Figure 6 shows the distribution of input heat contained in the various outstreams.

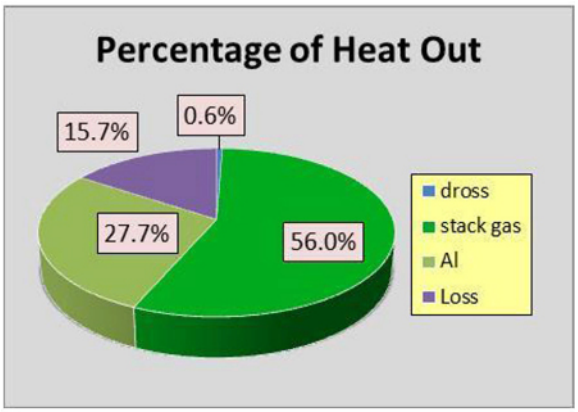

Figure 6. Distribution of input heat among products for basis-case operation. The stack gas contains about twice the heat of the molten aluminum.

A review of the effect of basis-case independent parameter values on thermal efficiency suggests that some process modifications could improve the fraction of heat used for melting [16]. The excess oxidant was cut to 3%, the leak air to 1 m^3/min, the heat loss to 70,000 kJ/min, the stack gas temperature to 1150 °C, and the aluminum bath temperature to 750 °C. Figure 7 shows the after-change results. The improvement was noticeable, but the stack gas still carries out over 51 % of the available heat.

A significant implication of the basis-case model is the assumption that none of the independent variable values are affected by changes in other independent values. While this assumption might be valid for small changes, it probably isn't for larger ones. Therefore, the model contains selected options for substituting an equation for an independent value, thus making

one of the independent values a function of another one. For example, the stack gas temperature of 1170 °C for the basis case is clearly going to be a function of the flowrate of fuel gas—the higher the flow, the less the residence time of the POC in the furnace. Hence an equation was developed to replace the value of the basis-case stack temperature in the model to improve the validity of the results.

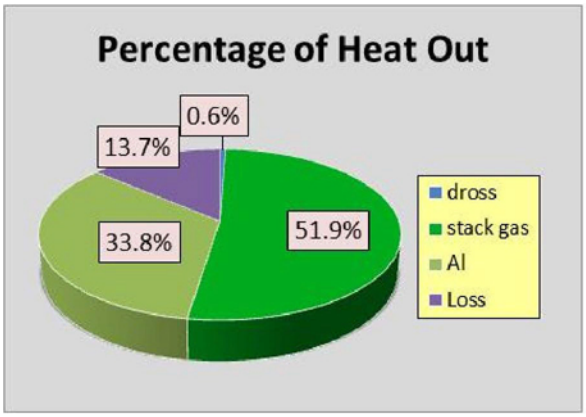

Figure 7. Distribution of input heat among products after minor improvements in the basis-case operation. The stack gas contains about 1.5 times the heat of the molten aluminum. Compare to Figure 6.

Process simulations displayed an interesting outcome—a minimum value in the specific energy consumption. The specific energy consumption starts out high at low firing rates because the heat loss is a large fraction of total energy input. A minimum is reached of 4090 kJ/kg (at 13 m^3 fuel/min, with a stack gas temperature of 1137 °C). Firing rates above this value cause the stack gas to rise in such a way that its heat content dominates the percentage of heat out of the furnace. Although the aluminum melt rate continues to increase, the thermal efficiency of the process drops (to 4295 kJ.kg at 17 m^3/min fuel flowrate). The existence of minimum specific energy consumption is observed in practice [17].

The Structure and Operation of the Extended Basis-Case Model

Figures 4 and 5 show flowsheets that include the most commonly used methods for improving thermal efficiency—oxidant and scrap preheating. The model is set up to look at each method *independently* to develop a quantitative relationship between oxidant and scrap temperature, and specific energy consumption.

In either method, recycling heat from the stack gas to the furnace means that at a fixed melt rate, less fuel is required, and hence less stack gas is generated. The law of diminishing returns applies here, in that less stack gas means less heat is available to be recycled. As a result, the relationship between the specific energy consumption and scrap (or oxidant) temperature can be non-linear.

Scrap Heating

Scrap heating was modeled by keeping the basis-case conditions intact *except* the scrap temperature. Passing none, some, or all of the stack gas through the heat exchange stack was used a technique to simulate a range of gas-scrap heat transfer efficiencies. The heat loss from the scrap heating shaft was arbitrarily set as 5000 kJ/min. When none of the stack gas is directed though the scrap HX, the heat loss in the stack drops the warm exhaust gas temperature from 1170 °C to 1150 °C*.

Simulating the effect of scrap heating requires selection of one of two possible basis choices: constant firing rate (i.e., 14.5 m^3/min fuel flow), or constant melting rate (120.5 kg/min). In the first case, heating the scrap causes an increase in the melting rate, which causes an increase in the denominator of the specific fuel consumption factor. The second choice causes a decrease in the firing rate, which causes a decrease in the numerator of the factor. The model allows use of both basis choices. However, the second choice requires a backward oriented calculation because the aluminum melt rate must be changed from a dependent to an independent variable, while the opposite is true for the firing rate variable. The methodology for accomplishing this is to employ Excel's Goal Seek tool, which searches for an input that will give a specified output [18]. For either choice, two Excel add-in tools (Multicalc and Multigoal) [1] are very useful. Figure 8 shows the results for melting 120.5 kg/min. Over the range displayed, the stack gas temperature dropped from 1150 °C to 875 °C. Equipment may limit the upper temperature of heated scrap.

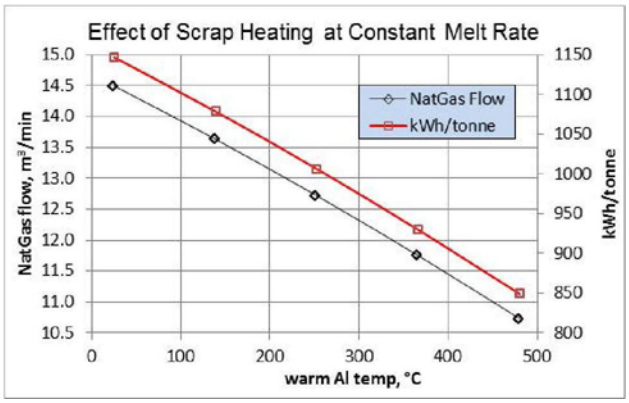

Figure 8. Effect of scrap heating on specific fuel consumption and firing rate at a constant melting rate of 120.5 kg/min. Heating the scrap to 480 °C decreases the fuel consumption by 26 %.

Oxidant Heating

The oxidant heating model was similar to that of the scrap heating model in that the basis-case conditions were kept intact *except* for the oxidant temperature. The HX heat loss was 5000 kJ/min. Figure 9 shows the results of a simulation at a constant melting rate of 120.5 kg/min. Over the range displayed, the stack gas temperature dropped from 1150 °C to 620 °C. Equipment may limit the upper temperature of heated oxidant.

Additional simulations

The model permits consideration of two other techniques that have been suggested for improving thermal efficiency in aluminum melting furnaces. First, melt stirring to lower the bath

* The warm exhaust gas temperature calculation requires use of the quadratic formula in the heat balance.

surface temperature [10, 19], and second, oxygen enrichment of the combustion air [4]. The first technique allows a greater temperature difference between the POC and bath, thus enhancing the rate of heat transfer to the bath, while decreasing the amount of dross formed. The second technique takes advantage of the decrease in amount of stack gas by lowering the percentage of nitrogen.

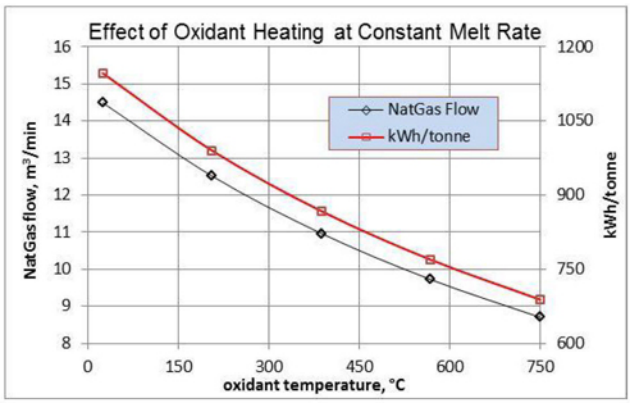

Figure 9. Effect of oxidant heating on specific fuelconsumption and firing rate at a constant melting rate of 120.5 kg/min. Heating the air to 750 °C decreases the fuel consumption by 40 %.

The relationship between bath stirring and firing rate requires plant data to improve the formulae used in the model. Oxygen enrichment produces a higher flame temperature, and may require a special burner to avoid creating a "hot spot" in the bath that can enhance dross formation.

Conclusions

Developing a process model can seem daunting. However, by following certain guidelines, a decent Excel model can often be developed that's suitable for simulation purposes.

1. Study the process to collect data on stream properties (flow, composition, and temperatures.
2. Measure the amount of energy actually used.
3. Determine which variables are under operator control, and how well the control points are attained.
4. Define an (over) simplified flowsheet as a starting point.
5. Prepare a material and heat balance for the process, and compare values to those measured.
6. Add features to the model to make it more realistic.
7. Test the model, then repeat step 6 until satisfied.

One essential of a good model is that a co-worker can understand its features, how it's organized, and the rationale behind the cell formulas. Another essential is built-in flexibility so it can be changed for different applications. These features mean liberal use of cell comments and an embedded help text.

References

1. Arthur Morris, "Improving Thermal Efficiency in Aluminum Scrap Melting", *Industrial Heating*, (May 2014), 41–45.

2. B. Wayne Bequette, *Process Control: Modeling, Design and Simulation* (Prentice Hall, 2003), 800 pages.

3. Babatunde A. Ogunnaike and W. Harmon Ray, *Process Dynamics, Modeling, and Control* (Oxford University Press, 1994), 1260 pages.

4. V. Y. Gershtein, C. E. Baukal, and R. J. Hewertson, "Oxygen-Enrichment of Side Well Aluminum Furnaces", *Industrial Heating*, (May 2000), 41–46.

5. P. E. King, J, J, Hatem, and B. M. Golchert, "Energy Efficient Operation of Secondary Aluminum Furnaces", *Furnace Systems Technology Workshop: Emerging Technologies and Energy Efficiency*, P. E. King and S. K. Das, eds., TMS, (2006), 9–14.

6. METSIM—The Premier Steady-State & Dynamic Process Simulator. www.Metsim.com.

7. AspenTech—Software That Optimizes Process Manufacturing. www.Aspentech.com.

8. ANSYS—Fluent CFD Simulation Software. www.ansys.com.

9. Arthur Morris, Gordon Geiger, and H. Alan Fine, *Handbook on Material and Energy Balance Calculations in Materials Processing*, 3rd Edition (Wiley/TMS, 2011), 604.

10. Brian Golchert et. al., "Improved Aluminum Melting Using Pumping", *Furnace Systems Technology Workshop: Emerging Technologies and Energy Efficiency*, P. E. King and S. K. Das, eds., TMS, (2006), 3–7.

11. Software: FREED, www.thermart.net

12. Wikipedia contributors, "Combustion". Wikipedia, the Free Encyclopedia (September 2014).

13. Arthur Morris, "Calculating the Heat of Combustion for Natural Gas", HeatCalc.xlsx. *Industrial Heating*, (September 2012), 28.

14. Arthur Morris, "Making a Material Balance", MatBalCalc.xlsx. *Industrial Heating*, (March 2013), 24.

15. Arthur Morris, "Making a System Balance—Part 2", SysBalCalc2.xlsx. *Industrial Heating*, (November 2012).

16. Cynthia K. Belt, Ray D. Peterson, and David Bequette, "Five Low Cost Methods to Improve Energy Efficiency on Reverberatory Furnaces", *Energy Technology 2010*, Neale R. Neelameggham et. al, eds., TMS, (2010), 71–78.

17. Cynthia K. Belt, "Save Money by Optimizing Your Furnace Fire Rate", *Industrial Heating*, April 2014, 4749.

18. Wikipedia contributors, "Goal seeking". Wikipedia, the Free Encyclopedia (September 2014).

19. Dominik Schroeder and Georg Dambauer, "The Latest Aluminum Scrap Recycling Plant Technology", *Industrial Heating*, (August 2014), 61–65.