Aluminum Melt Furnaces: Principles of Fuel Economy

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Abstract
The goal of this paper is to review basic principles that affect the energy efficiency of gas and oil-fired furnaces for melting and holding aluminum. Because there are so many different types and sizes of these furnaces, it is not easy to recommend the best way of operating every type, but some general ideas based on years of personal observations are offered for maximizing energy efficiency.

Analyzing the Heat Balance
What happens to the heat that is input to the furnace? A heat balance can be determined by measurements and calculations, and the results presented as a Sankey Diagram, or as a pie chart. From these typical charts we can see that waste gas or flue (chimney) losses are the most important loss of energy. Most furnaces have a very short dwell time for the combustion gases and they leave the furnace at high temperatures. This loss is high even when the furnace is in holding mode, and it is extremely high during maximum charging rate. There are various systems to recover this heat, which will be discussed later. Note that a large part of the flue loss is due to evaporation of water in the air and that resulting from combustion.

Fixed Losses mainly include wall and hearth losses due to heat transfer through the furnace walls, floor, and roof, as well as losses through openings. These losses are constant, more or less, depending on whether the furnace is at operating temperature or not, but these losses are the same regardless of production throughput. Therefore, maximum energy efficiency can be reached by increasing production as much as possible. This seems obvious, but we see many furnaces that are kept at high temperature when there is no throughput. Also, there are often bottlenecks to production due to the
charging methods, poor design of charge openings and equipment, and failure to make the best use of the operating cycle.

Keep in mind that the roof and upper walls may be well insulated to reduce these losses, but the hearth must not be well insulated. To keep liquid metal from passing through brick joints or cracks in the refractory, we depend on a freeze plane, so that the liquid will freeze before it can pass out of the furnace. Insulation would change the freeze plane and result in a dangerous bleed out. Location of the freeze plane is calculated based on liquid metal temperature, ambient air temperature, and insulating values of the refractory.

![Freeze Plane](image-url)
Since so much of the heat loss is relatively fixed, regardless of throughput, factors, it becomes clear that increasing the throughput or production on any particular furnace will increase overall unit efficiency --- BTUs or Kilocalories per pound or kilogram. Data and experience confirm this conclusion. Consider the following diagram:

This actual data shows how increasing the production through the furnace will greatly reduce the fuel required per unit of production. We will need to look for ways to increase production through the furnace.

**How Heat is Transferred to the Load**

Improving efficiency requires consideration of the types of heat transfer to the load: radiation, conduction, and convection. All three types are at work, but in different ways.

Radiation and convection transfer heat from the flame to heat the refractory lining and the surface of the bath. The refractory then radiates more heat to the bath. (This is why these furnaces are sometimes called reverberatory or "reverb.") If there is scrap or ingots exposed above the bath level, it also is heated by the radiation and the convection of hot combustion gases.

When the charged metal is below the level of the liquid bath, heat is transferred from the liquid by conduction and convection. Here we begin to have problems with the heat transfer. Aluminum is usually considered a good conductor of heat, but in fact the amount of heat conducted from the liquid to the charge is very poor. To effectively transfer heat from the liquid requires convection --- circulation of the liquid metal within the bath.
Inside Reverb Melter

Reverb Furnace Diagram (Lead)

Metal Circulation In Reverb
Forced vs. Natural Metal Circulation

Natural circulation occurs due to the differences in temperatures within the bath. In an open-hearth furnace, one with an open charge well, the metal surface in the well is cooler than the surface inside, and this temperature difference causes some circulation of metal. While the flow rate is relatively small, it greatly improves the charge rate as long as the open arch of the well allows surface metal movement.

When greater rates of circulation are desired, there are several different types of machines to increase circulation rate:

**Pumps.** A shaft and impeller are usually driven by an air motor (but may be electric). All components that contact the metal must be made of ceramics, and therefore are very fragile. Abrasion also reduces the life of components. One man who was responsible for pump maintenance advised that 7 spare pumps in various states of rebuild must be kept for every pump in service.

Some operations require transfer of liquid metal to a pot or crucible, and a similar pump may be used for this purpose.

**Electromagnetic Pumps.** These pumps have no moving parts but propel the metal upward by electromagnetic force. All wetted parts are still ceramic, and these are not widely used.
**Electromagnetic Stirring.** An electromagnetic stirring device is installed under the furnace bottom or on the side wall and circulates the metal inside. While more capital-intensive, these units are relatively trouble-free.

All of these have the additional advantage of making the temperature and alloy mix more uniform by stirring it. While these systems increase charge rate, there are disadvantages in terms of cost, both initial investment and in continuing maintenance.

**Batch vs. Continuous**

Whether forced circulation is recommended depends in part on whether the furnace is operated in "batch" or "continuous" mode.

**Batch** operation involves filling the furnace with melt and then transferring all or most of the charge, either to a billet casting machine or to another "holding" furnace. In this case the remaining metal -- or "heel" -- is at a relatively high temperature until the next charge is loaded into the furnace. When this charge is loaded, bath temperature drops near the freezing temperature, and the furnace should go to highest firing rate. Because of the low temperature, metal will solidify in the pump, and forced circulation by pump is not possible; if a pump is installed it must be removed to prevent damage.

**Continuous** operation furnaces remain relatively full of molten metal, with a steady stream of metal drained or pumped out to a transfer container or to a continuous caster of some sort. Metal level is maintained by frequent re-charging, of course taking care to maintain correct alloy composition and temperature. Continuous operation furnaces have a steady level and high metal temperature, and therefore are very suitable for forced circulation by pumps, as well as pump transfers from the furnace.

Forced circulation by electromagnetic stirring is practical for both types of operation, as the unit does not contact the metal directly.

**Charging Methods and Charge Mix**

The procedures for charging the furnace will vary widely according to the type of furnace and the nature of the charge mix:

**Ingots** are easily charged, but the presence of water inside must be considered. Cast ingots usually have shrinkage cavities which may contain water. To avoid explosions, ingots must be preheated before being charged into the liquid bath.
Butt scrap and cropped billet ends are easy to handle and charge due to their density, but care is required since water and oxide may also cause explosions. It is best to charge this scrap on top of other charge to allow it to dry.

Small extrusion pieces are also easy to handle and charge due to high density, and these may be charged through a door or into a side well. Chopping extrusions to a short length is good for transport, handling, and charging but requires the correct chopping machines.

Long extrusion scrap is the most difficult to get into the furnace fast enough for a good charge rate. The best solutions are an open top melter, a large door for charging, or an open charge well.

Baled extrusions are compact and dense, which is good for transport and ease of charging. However, melting is very slow because hot liquid metal can't penetrate the bale. The bales may also have undesirable content such as iron hidden inside.

Chips from sawing are extremely difficult to melt without high melt loss to oxidation. If submerged under the liquid, the chips may fuse together and require an extremely long time to melt. If put on top of the charge, most chips will burn completely. The best solution is to feed them into a circulating pool of liquid metal, or else reclaim them in a rotary salt furnace.

Personal opinions also matter, because people may have different experiences and different equipment. The procedures for batch-type furnaces will be different from those of continuous-type.

Continuous-type furnaces always maintain a full bath, adding small batches of charge according to the amount of hot metal being taken out. Therefore charging these small batches is not complicated and can be done through standard furnace doors or charge wells.

Batch-type furnaces present a different set of problems, especially when the percentage of scrap in the charge mix is high. Since scrap is usually of low density, charging a large amount will dictate the design of the furnace. Wide charge doors, open wells, and even removable-top designs are suited to large amounts of scrap. Putting long scrap into a charge door is difficult unless a charge machine is available. If the charge door is left open more than a very few minutes, the furnace will be cooled off too much and recovery take a long time. Open-top charged melters are a great solution but investment cost and space required are issues.
For the typical extrusion company, a furnace with large door and open charge well seem the best solution.

Keeping in mind the low density of extrusion scrap, and the large amount of scrap we needed to melt, transporting it to the furnace by loader fast enough was a problem. We built a ramp with sides, like a cattle loading ramp, so that the scrap could be pushed into the hearth instead of carried. It was a great solution.
The next issue for a batch furnace was the **sequence of charging**. After much trial and error, here is the sequence we decided on:

1. Immediately after the transfer of metal to the holder is complete, begin charging light scrap as fast as possible. The furnace is at its hottest point, and the scrap will melt quickly.
2. As soon as scrap melting slows down, charge the next heaviest scrap. (Butts in the case of an extrusion plant.)
3. At this point it is time to begin charging the ingots through the door. When the furnace is full, close the door, put burners on high fire, and take a break while melting is completed.

In our experience this charge sequence resulted in the lowest total cycle time.

The following pictures show different types of charging systems for scrap and ingots, designed to save energy by speeding up the charging cycle:
**Combustion Ratio Control and Burner Adjustment**

Good control of combustion fuel-air ratio is especially important in a reverb-type furnace. Since the combustion gases do not stay in the furnace more than a few seconds at most, a rich mixture (too little air) will still be burning and transferring heat after it has left the furnace and entered the chimney. On the other hand, a lean mixture (too much air) absorbs much of the heat just to heat the excess air. A correct ratio is needed to provide the best flame pattern and maximize efficiency.

If the system uses heat recovery to pre-heat combustion air, it is absolutely essential to have ratio controls that operate on mass flow measurement, in order to adjust to varying air temperatures. In fact, mass flow ratio controls are recommended for even simplest furnaces in place of the old, primitive cross-connected ratio controls.

**Furnace Pressure Control**

Pressure inside the furnace must be kept as close as possible to absolute zero. If there is negative pressure, cold air will be sucked in and efficiency is reduced. If there is positive pressure, flame will come out of the doors and other openings, damaging the structure.

A simple test of furnace pressure is to take a small tissue paper and hold it near a door edge, and its movement in or out will indicate the pressure.

Pressure control may be made using a damper on the exhaust chimney. I recommend a sliding refractory damper, operated by a servo motor.
Dross and Oxide Build-up

Since heat is transferred into the bath by radiation and convection, a heavy dross layer will reduce heat transfer and therefore reduce the charge rate and the energy efficiency. Clean the dross from the furnace on a regular basis.

Waste Heat Recovery Systems

There have been many systems used to recover the heat that leaves the furnace through the chimney. Most common are systems to preheat the charge metal or to preheat combustion air. One plant added a small boiler after a charge preheater in order to recover even more heat.

**Tube-type recuperators** are installed after the chimney; hot gases pass around the outside of the tubes and combustion air inside the tubes to be preheated. Problems with this system include tube life, due to the high temperatures and corrosion.

**Ceramic bed recuperators** also preheat combustion air. There are two sets of burners which alternate...
between firing and serving as exhausts; exhaust gases pass through ceramic beds, preheating the ceramic media. Then the sets of burners reverse the function, with combustion air passing through the media to be preheated. These systems are reasonably practical and reliable.
**Ingot preheaters** pass the hot gases through a chamber where ingots are placed for preheating. In addition to energy savings, safety is improved because many ingots have water entrapped in "shrinkage cavities" and could explode if charged cold into the bath.

**Scrap preheaters** vary in design, either by charging scrap into a specially-designed chimney, or by taking the gases through a system such as a rotary heater.

**Measurement and Control**

It is critically important to high efficiency operation that energy consumption be regularly measured and controlled. Each furnace should be equipped with a gas or oil meter, the consumption should be read weekly, and the efficiency --- heat value per unit of production --- be calculated and reported to management regularly.

This system allows determination of best practices and also indication and diagnosis of equipment malfunctions.

**Summary**

Getting the maximum efficiency from an aluminum melting or holding furnace is no mystery if one pays attention to these simple laws of science. Observe the furnace, measure the performance, and continue to make changes that will pay off in great cost savings.