Performance Analysis of the Aluminum Casting Furnace

R. T. BUI and J. PERRON

The casting furnace plays a central role in the production of aluminum. Its design and operation are complex and involve some 450 parameters. There is a need for a model to predict and analyze its performance. We propose a simplified model in which each main component of the furnace is treated as a 1-D heat conduction medium. Based on the equations of conservation of mass, energy, and chemical species, complemented by the equations of conduction and the Hottel’s formulation of radiative heat transfer, this dynamic model can simulate any sequence of operations such as loading, heating, stirring, skimming...that constitutes a batch, and can take into account other operational details such as the opening of doors. It is validated on a real furnace, then used to predict furnace performance in other modes of operation, and also to determine an optimal fuel flow that minimizes a chosen cost function.

I. INTRODUCTION

The aluminum casting furnace plays a central role in the production of primary aluminum. Its place in the process is between the potline where liquid aluminum is produced by electrolysis, and the castshops where the liquid metal, after being appropriately prepared and brought to the right temperature, is poured into the molds to make ingots or other products. The role of the furnace is to receive the liquid aluminum from the electrolytic cells, bring it to an appropriate temperature, and hold it there for alloy preparation and for casting. The furnace also receives a solid charge made of solid aluminum of various sizes such as extrusion butts, ingots, and logs, to be melted into the liquid metal. In addition to holding and melting, the aluminum also undergoes a cleaning operation by action of chlorine, known as fluxing. To improve the heat transfer, the metal is stirred by the action of a jet of inert gas such as nitrogen; and the dross formed on the surface is skimmed by mechanical action. Note that chlorine, besides its role as fluxing agent, also provides a stirring action similar to the one provided by the inert gas. This type of furnace is often called melter-holder.

Melter-holders consume large amounts of energy at a low efficiency. Figures of specific consumption commonly encountered are in the order of 4.5 to 6 megajoules per kilogram of aluminum melted. Of this energy, usually no more than 20 pct actually reaches the metal either for melting or holding purpose.

Furnace designers are interested in improving the design in terms of energy efficiency and productivity, while the operators will want to know what the effects of changes in the operating procedures will be. We are speaking here of changes in the sequence of operations that constitutes a batching cycle, or changes in the duration of each of these operations, or changes in the size of the charge, and also changes in the ways of performing an operation, e.g., a continuous stirring of the liquid metal vs a discrete stirring or a closed door operation vs open door. The purpose of this work is to build a mathematical model, of relative simplicity and not too expensive to run on the computer, and capable of providing an answer to these questions. During the past months, we have endeavored to address a number of such questions using a preliminary version of the model, and the results have been presented in a technical meeting. This paper gives the final version of the model along with its validation and applications.

The number of design and operating parameters involved in the melter-holder is indeed large, in the order of 450. With such a high degree of freedom, it is difficult to make decisions based only on experience and intuition.

The physical phenomena involved are conduction, convection (natural and forced), and phase change in the metal; radiative-convective heat transfer, combustion, and gas flow in the combustion chamber; and heat transfer by all three modes in the roof and the floor of the furnace.

II. THE FURNACE AND ITS OPERATION

Figure 1 gives the cutaway views of the furnace to be simulated, in the axial and the transverse directions. The furnace can be seen as made of four main components: the gas in the chamber, the metal, the roof, and the floor. The gas (gaseous fuel and air) comes in through burner (4) and exits through stack duct (3). The solid scrap (10) is introduced through doors (5) into a liquid heel, then preheated before more liquid metal from crucibles is introduced through siphon (11) up to level (9). The roof (1) (2) and the floor (6) (7) (8) are made of steel shell, insulation materials, and refractory linings. At casting time, the furnace is tilted and the metal is poured into the mold through spout (12). This description is taken from a 72-ton melter-holder in operation at the Jonquière works of Alcan Smelters and Chemicals Ltd. Approximate dimensions are 10 m in length, 4 m in width, and 3 m in height. The charge is usually made of about 10 tons of solid and 62 tons of liquid metal.

A typical schedule of a batching cycle is given in Table I. The solid charge is loaded into a liquid heel, then heated for about an hour. After a short pause, liquid metal is siphoned in and heating continues. A pause follows, then stirring with a jet of inert gas takes place. Another hour of heating brings the liquid metal to the desired temperature. The alloying operation is next, followed by a second stirring and fluxing. Finally, all doors are open for a skimming run along the whole furnace length, after which the batch is ready for casting.
III. THE MODEL

The purpose is to build a model that helps simulate and analyze the energy flows inside the furnace, using the global properties of each of its four main components, namely the gas, the metal, the roof, and the floor. The model must be dynamic to simulate a sequence of operations constituting a batch.

Khalil\textsuperscript{2} considers three types of furnace models according to the nature of the data input and output, as summarized in Table II. All three types require as input the mass flows, enthalpy flows, and boundary conditions. In addition, type I models need the average convective heat transfer coefficients and yield the average values of temperature and flux. Type II models go further and require a macro flow pattern as well as the local convective heat transfer coefficients and yield one-dimensional temperature gradients. Type III models are the most comprehensive; they require a detailed flow pattern and yield spatial temperature distributions.

A survey of the literature shows that the only melting furnace models built to date\textsuperscript{3-7} are of type I at the most. The model elaborated in this work is of type II.

We treat each main component of the furnace as a one-dimensional heat conduction medium. The thickness and the area of each such medium are taken from the actual geometry of the furnace. The physical properties (conductivity, density, specific heat) are taken as the weighted average of those of the various layers forming the medium. For the gas, plug flow from burner end to duct end is assumed. This approach leads to a model that requires little computer time, and makes it practically feasible to run whole series of simulations, enabling us to predict and compare furnace performance under various operating conditions.

Figure 2 defines the symbols used to identify the various components of the furnace and their interfaces. Capital let- ters refer to interfaces while numbers indicate the components. Table III gives the meaning of each such symbol. Note that during stirring, alloying, fluxing, and skimming, some or all five doors are opened for a period of time. Hence the heat flow through the inner roof surface $Q_{ev}$ must be split into two parts, namely $Q_{evr}$ for heat flow through the roof proper, and $Q_{ee}$ for heat flow through the open doors. The latter is calculated by assuming that the wall of the building seen by the furnace through its open doors, is a black surface capturing all the heat it receives. Note that when the doors are open, the form factors used for the closed-door furnace are no longer appropriate and therefore have to be recalculated.

As for stirring and fluxing, we assume that the time rate of decrease of the enthalpy gradient in the liquid metal is a

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(a) -- longitudinal, (b) -- transverse. 1, 2: roof, 3: stack duct, 4: burner, 5: doors, 6, 7, 8: floor, 9: melt level, 10: solid metal, 11: siphon, 12: spout, and 13: thermocouples.