Computer applications in the field of furnace design

V S PAKALA

Department of Metallurgy, Regional Engineering College, Rourkela 769 008, India

Abstract. The development of mathematical models of furnaces is briefly reviewed. The basic processes taking place in furnaces and the problems associated with their mathematical formulation and the necessary assumptions are discussed. The difficulty of determining the process parameters, and the methods of their estimation are included. Applications of mathematical models for the study of cooling of ingots, heating of steel, cowper stoves and for the study of erosion of refractories are also discussed.

Keywords. Heating furnaces; mathematical models; process parameters; furnace design

1. Introduction

At the beginning of the present century, a Russian scientist, Groume-Grjmailo, placed the transparent model of a furnace upside down and passed water through it so as to study the flow of combustion products through the furnace. He could thus formulate the principles of design of some furnaces. This probably was the first scientific approach to the design of furnaces, and also the beginning of model studies of furnaces.

With the developments in the field of model studies it soon became evident that a clear understanding of the interaction of various parameters, influencing the process under study, is necessary for setting up an appropriate model. These interactions are best expressed in the form of mathematical relationships i.e. mathematical models.

The development of a mathematical model depends on a knowledge of the laws of behaviour of the system being studied, the capacity of expressing these in the form of mathematical equations, and the ability to solve them.

The basic processes, taking place in furnaces, are known for a long time, but the difficulties associated with the solution of the partial differential equations, with the complex boundary conditions involved, restricted the use of mathematical modelling of furnaces. Thring (1952) made some simplifying assumptions to calculate the heat transfer in open hearth furnaces and this probably is the beginning of mathematical modelling of furnaces.

With the developments in the field of digital computers, the interest in mathematical modelling of furnaces has increased significantly.

In this article, models of only heating furnaces i.e. furnaces where the charge does not undergo any chemical changes, are considered.

2. Types of models

Mathematical models based on the fundamental laws of behaviour of the system are called process models. These are concerned with the activity between start and finish of

the process and describe, among other things, the cause of the variability of the process time. The activities, in general, are continuous and the model consists of equations relating rates of change of variables, describing the system, to their current values i.e. the model consists of differential equations.

In some cases, e.g. logistics of assembly processes, models generating the time history of process are known as simulations. In these models the matters of interest are the start and finish of the process. The model determines the complete history of events from these events and the logistic laws.

Process models serve many purposes, including our understanding of the process and indicate areas where information is limited and further research desirable. In engineering they facilitate experiments which are otherwise not feasible since practical experiments on full scale iron and steel making units are difficult and expensive. Engineering modifications are also costly and almost impossible to examine experimentally on full scale plants. However, once a mathematical model is formulated and verified by plant measurements, it is in principle comparatively easier to carry out the necessary computer experimentation. Even if full scale experimentation is needed it can be restricted to a minimum number of crucial cases.

It must be recognized that every model is imperfect in one aspect or the other, either due to simplifications of the process mechanism that are necessary to evolve a practical model, or due to inadequate understanding of the mechanisms.

3. Formulation of furnace models

For heating furnaces where heating of the charge to a given temperature is the main objective, the model must be able to predict the internal temperature distribution of the charge at any given time. The temperature distribution in a solid charge is given by the conduction equation

$$\frac{1}{\rho c} \cdot \frac{\partial t}{\partial \tau} = K \nabla^2 t, \quad (1)$$

where K is the thermal conductivity of the material, ρ the density, c the specific heat, t the temperature and τ the time. This equation has to be solved with the appropriate boundary and initial conditions to obtain the temperature distribution.

The boundary conditions usually give the heat flux to the surface.

$$q = -K \frac{\partial t}{\partial x}, \text{ at the boundary.} \quad (2)$$

For some simple boundary conditions, (1) can be solved by analytical methods if K , ρ and c are independent of temperature. But in actual practice the boundary conditions are not simple and the values of K and c are dependent on temperature. In such cases only numerical solutions of the equation are possible, the method of finite differences being the most common. These methods have been described by Dusenberre (1961). Thomas *et al* (1984) analyzed the different methods and concluded that for simple geometry of the body, finite difference method is the most suitable. Tocher (1970) briefly analyzed the errors involved in these methods.

The value of q in (2) depends on the rate of heat transfer to the surface of the body from the furnace. This consists of radiation from flame, radiation and convection from the combustion products and radiation from the refractory walls. For precise calculation of the internal temperature of the body, precise formulation of these external heat flows is necessary.

The problems associated with mathematical description of flames were analyzed by Beer (1972). Furnaces usually have turbulent diffusion flames, and it is reasonable to assume that the development of the flame depends only on the mixing of fuel and air. The description of a turbulent flow system, with an exothermic chemical reaction, in terms of spatial distribution of velocity, concentration and temperature requires the simultaneous solution of partial differential equations for mass, momentum and energy transfer. Patankar and Spalding (1970) and Gosman (1969) discussed the solution of these equations. Apart from the complexity of the solution, difficulty arises with the values of the turbulent transport properties, which are not constants for the medium. Added to this is the difficulty to evaluate the development of luminosity in flames.

Most models developed for fuel-fired furnaces use simplifying assumptions for calculation of the external heat flow. Usually the furnace gases are assumed to be non-luminous having uniform temperature within the furnace chamber. In long furnaces, like pusher re-heating type, the furnace may be considered as consisting of a number of isothermal zones. If the temperatures of gas, refractory surfaces and charge surface can be represented by their respective mean temperatures, the heat transfer to the charge can be calculated by standard methods (McAdams 1954; Averin *et al* 1969; Davies *et al* 1970). Salter and Costick (1972) applied experimentally determined flame parameters for modelling a re-heating furnace. Fitzgerald and Sheridan (1970) used measured surface temperature of the charge to calculate the internal temperature distribution.

4. Process parameters

The necessity of considering the variation of physical properties of steel with temperature was mentioned earlier. A fairly comprehensive source of data is a compilation by BISRA (1953). These are experimentally determined values. For temperatures above 1000°C, an error of 8–15 % can be expected.

While heating steel, in most of the cases a layer of scale forms on the surface. Reliable data on the properties of scale are not available.

The difficulties involved in calculating the heat flow to the charge were mentioned earlier. In practice either simplifying assumptions have to be made or heat transfer parameters have to be determined from measurements on actual furnace.

The heat flux to the charge can be represented as either

$$q = \sigma F(T_f^4 - T_m^4) + h(T_f - T_m), \quad (3)$$

or
$$q = H(T_f - T_m), \quad (4)$$

where T_f and T_m are the temperatures of furnace and the surface of the metal respectively, σ the Stefan-Boltzman constant, F is a radiation factor, h the heat transfer coefficient by convection and H is the combined heat transfer coefficient. The value of T_f is usually taken as the temperature indicated by the thermocouple located in the furnace chamber. From the measured temperatures of the metal the values of F and h or H are computed by solving the inverse heat transfer problem.

Lambert and Economopoulos (1970) described a method of using probes for determining the heat transfer coefficients. The heat transfer coefficients by convection can be determined with the help of isothermal physical models by making use of an analogy between heat transfer and mass transfer. From the measured mass transfer coefficients the heat transfer coefficients are computed. Davis *et al* (1970) used evaporation of naphthalene and Choudhury and Mukherjee (1979) used transfer of CO₂ from the gases to filter papers soaked in NaOH solution to measure mass transfer coefficients.

5. Application of mathematical models for furnace design

A few of the applications of mathematical models for design of furnaces are discussed below.

5.1 Solidification of ingots

Although solidification of ingots is not a process taking place inside a furnace, the knowledge of internal temperature distribution of hot ingots is necessary for subsequent heating. By optimizing the stripping time and subsequent transit time before charging the ingots into soaking pits, considerable energy can be saved in the soaking pits. This problem was studied by Jackson *et al* (1944) using analogues and by Sargent and Slack (1954) using numerical methods and others.

The peculiarity of the solidification process is the liquid-solid transformation, which is accompanied by the liberation of latent heat. The governing differential equation becomes

$$\rho C \cdot \frac{\partial t}{\partial \tau} = K \nabla^2 t + \rho L \frac{\partial f_s}{\partial \tau} \quad (5)$$

where L is the latent heat and f_s the fraction of solid. This equation can be solved by applying the equivalent specific heat method where the specific heat is increased by an amount equivalent to latent heat in the solidification zone. This method is most widely used. Other assumptions made in formulating the model are: (a) the mould is filled instantaneously; (b) initially there is good thermal contact between the metal and the mould, for 2–3 min, when the heat transfer from metal to mould is by conduction; (c) very soon a solid skin is formed on the ingot, which shrinks away from the mould, leaving an air gap. Further heat transfer is by radiation only; (d) heat losses from the outer wall of the mould are uniform.

Sevrin (1970) calculated the solidification time of ingots and showed that mould thickness and mould temperatures, within limits, have no significant effect on the solidification time. Cherapanov and Kalashnikova (1971) claimed significant saving in the mould weight, based on these calculations.

Making use of the above assumptions the solidification of a 21-tonne ingot was earlier carried out by mathematical modelling (Pakala 1975). The calculated surface temperature was compared with values measured on an ingot, after stripping by optical pyrometer. The results showed good agreement, with a difference of about 10°C just

after stripping. But with further cooling the measured temperatures were lower than the calculated values. This was assumed to be due to scale formation on the ingot which was not considered in the model.

5.2 Heating of steel

Models for heating of ingots and billets were developed by Fitzgerald and Sheridan (1970), Collins (1970), Massey and Sheridan (1971), Massey *et al* (1973) etc. In all these models the furnace gas temperature was assumed to be uniform and the external heat transfer parameters were estimated from measurements on furnaces.

One of the factors to be considered in heating of massive steel ingots and billets is the heating rate. Too fast a heating rate results in a large temperature differential in the part with accompanying thermal stresses. In order to develop a satisfactory heating schedule for cold ingots a model was developed by the present author (Pakala 1975). Here the furnace gases were assumed to be at uniform temperature. The furnace walls were assumed to be perfect reflectors of radiation. This assumption was based on the fact that the wall temperature does not vary much with time and the heat conducted away through the walls is of the same order as the heat received by the walls by conduction.

The heat transfer parameters were calculated using equations reported in literature (Averin *et al* 1969). Variation of thermal conductivity and specific heat was accounted for. The mean gas temperature was calculated for every time step by iteration, assuming that

$$\text{Heat input through fuel and preheated air} = \text{Heat transferred to metal} \\ + \text{wall losses} + \text{waste gas losses.}$$

The fuel gases were assumed to leave the furnace at the mean gas temperature. Restrictions were incorporated in the programme, to ensure that the fuel rate does not exceed a given maximum value, and that the temperature difference between the surface and centre of the ingot does not exceed a given limit while the temperature of the ingot is below 500°C at the centre.

The minimum time of heating of 10 tonne ingots was calculated taking into account a two-dimensional heat flow. The heating schedule was adopted for an industrial unit and the ingots were found satisfactory for subsequent rolling. By this a 10% saving in heating time was achieved.

Chopdar *et al* (1980) calculated the heating time for annealing of open coils of steel strip under controlled atmosphere, and Padhy (1982) calculated the same for tight coils using mathematical models. Both these results were used for design calculations of hood annealing furnaces.

Fitzgerald and Sheridan (1970) described design modifications carried out on a reheating furnace based on the results of mathematical models.

5.3 Cowper stoves

A detailed model of Cowper stove was described by Hoffman and Kappelmayer (1970). Rakesh Kumar and Sugavanam formulated a simplified model of Cowper stoves, for evaluating the effect of fuel rate, duration of on-blast and on-gas periods etc on the performance of stoves.

5.4 Refractory erosion in blast furnace

Erosion of refractories in the hearth of a blast furnace, giving rise to formation of salamander is of primary importance from the point of view of campaign life. Paschkiss and Mirsipassi (1954) considered this purely from the heat transfer point of view and solved the two-dimensional steady state conduction problem on electrical analogue. They considered that only liquid iron can erode the refractories and that the salamander can penetrate to the level of 1150°C isotherm. Das (1981) calculated the isotherm for blast furnace at Rourkela. Singh *et al* (1982) reported monitoring of B.F. hearths by temperature measurements at TISCO.

Yoshikawa and Szekely (1981) considered the problem taking into account convection currents in the hearth. Bandak (1973) described a model for estimating the erosion of lining in the bosh and stack regions of blast furnace.

6. Conclusions

At the present state of knowledge, the mathematical models of furnaces, particularly those involving combustion of fuel, are far from perfect because of the difficulties involved in modelling the external heat transfer. Hence any model set up requires verification on industrial units. Despite these difficulties, considerable information can be obtained from these models for design and operation of industrial furnaces, and can be considered as a necessary tool for improvement of design and performance of furnaces.

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