Conference Paper

The Comparison of Two Calculation Methods of Billets Heating in Furnaces with the Help of Zone and FVM Methods

V. Lisienko, G. Malikov, and A. Titaev

Ural Federal University (UrFU), Ekaterinburg, Russia

Abstract

The comparison of two modelling methods for radiation heat exchange – finite volume and zonal methods – has been provided. The mathematical model of heating concast bars ring furnace has been created. Modelling of different heat modes of this furnace has been completed. In the result of modelling, it is shown that these methods demonstrate similar accuracy of obtained temperature values (not exceeding 50°C). The calculation time of FVM method is greater than zonal method to 13%, because recalculations of absorption coefficients by EWBM method is needed.

Keywords: radiation transfer, mathematical modeling, zonal method, discrete transfer zonal method

Corresponding Author:
V. Lisienko
lisienko@mail.ru

Received: 6 June 2018
Accepted: 15 June 2018
Published: 17 July 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the TIM'2018 Conference Committee.

1. Introduction

At recent time, mathematical modeling methods in connection with energy-intensive metallurgical processes, in particular, heating furnaces, has been widely used. Several approaches have been developed to modeling thermal radiation in heating furnaces. Commercial programs that combine the calculation of heat exchange with radiation with the calculation of hydrodynamics, combustion, and other physical processes usually use finite elements methods: the discrete ordinate (DOM) method, the finite volume method (FVM), and so on. The disadvantage of these methods is the one-time complete calculation of all heat fluxes in the system, based on rigidly defined boundary conditions. If you change at least one boundary condition, the calculation must be completely recalculated, which, together with the need to split the working volume by a small grid, makes these methods demanding for calculation time and computer capacity. Another approach (Zonal method) consists of splitting all surfaces and volumes of the system into a relatively small number of zones with further obtaining of some intermediate characteristic invariant from a part of the boundary conditions. Such characteristic, as a rule, is a matrix of the dimension NxN (where N is the number of allocated zones), called the Direct Exchange Area Matrix (DEA). This matrix, calculated one time, greatly simplifies the further calculation of the heat fluxes in the system for different sets of boundary conditions. Once calculation of DEA matrix may simplify further calculation under the different sets of boundary conditions, for example, finding unknown zone temperatures in the system of heat balance equations. Thus, the advantages of finite element methods are the simplicity of programming, the use of the same grid of elements as for methods of calculating hydrodynamics and combustion. But these methods are not optimized for multiple computations with different boundary conditions. The advantages of the zonal method are its computational accuracy, as well as the reduction of calculation for the cases when boundary conditions (boundary flows or temperatures) change. The drawbacks of this method include the fact that it requires the construction of a separate simplified grid of zones, as well as the increased computational complexity of determining DEA matrix that depend both on geometric relationships and on physical parameters (gases concentrations and furnace temperature).

In this article, a comparison of two methods for modeling heat exchange is considered: the finite volume method (FVM) [1, 2] and the improved zonal method (DTZM) [3, 4]. As the object of modeling, a heating furnace for continuously cast billets with a rotating bottom was chosen.

2. Theoretical Description of the Methods

2.1. The finite volume method

This method is described in sufficient detail in a number of papers [1, 2]. It is based on the solution of the heat transfer equation for a small cell of space (finite volume) P for each of the spatial directions. As known values, the previously calculated radiation intensities at the boundaries of a given volume I_x, I_y, I_z, as well as radiation from sources located inside a given volume b_P, are taken. The unknown intensity is the radiation intensity inside the volume P I_P. The general form of the equation for a finite volume:

$$a_p I_p = a_x I_x + a_y I_y + a_z I_z + b_p \tag{1}$$

where a_p, a_x, a_y, a_z are the coefficients determined by the geometric configuration of the finite volume and the chosen radiation direction.

The main computational difficulty of the method is to determine the coefficients in equation (1), and also to solve systems of such equations for all cells of the partition of the furnace space in parallel.

The coefficients for the orthogonal volume of the (Δx) × (Δy) × (Δz) and the chosen direction *l* in the general case are calculated by the formulas:

$$a_p = \Delta y \Delta z |D_x^l| + \Delta x \Delta z |D_y^l| + \Delta x \Delta y |D_z^l| + \Delta x \Delta y \Delta z \Omega^l \quad (2)$$

$$a_x = \Delta y \Delta z |D_x^l|, \quad a_y = \Delta x \Delta z |D_y^l|, \quad a_z = \Delta x \Delta y |D_z^l| \quad (3)$$

where the values D_x^l, D_y^l, D_z^l are determined by the chosen direction l and the solid angle of radiation propagation Ω^l.

In the general case, when the temperatures (and hence the intensities) are unknown, an iterative process of recalculating the intensities by formulas (1–3) is required to obtain the temperature field.

2.2. Improved zonal method

The zonal method is traditionally used to calculate thermal conditions in metallurgical furnaces. His development he received in the works of the group under the leadership of Lisienko VG. [3–5].

In the zonal method, several stages can be distinguished:

1. The dividing of the system to a number of surface and volume zones, characterized in the first approximation by constant physical parameters inside the zone (temperature, absorption coefficients).
2. The assignment of each of the zones of the system to its inherent optical properties (the emissivity for the surface zones, the absorption coefficient for the volume zones) based on the adopted radiation models for the surfaces of solids and gases.
3. Calculation of the matrix of generalized angular coefficients on the basis of the geometric interposition of zones and their optical properties by numerical determination using the formula:

$$\Psi_{ij} = \frac{1}{A_i} \int_{Ai} \int_{Aj} e^{-\tau(dA_j, dA_i)} \frac{\cos\theta_i \cos\theta_j}{\pi L^2} dA_j dA_i, \quad (4)$$

where dA_i, dA_j are the elementary areas allocated on the surface of the zones i and j;

A_j, A_i are the surface areas of zones i and j;

θi and θj are the angles between the normal to the surface of the bands and the ray connecting them with each other.

$\tau(dA_j, dA_i)$ is the optical thickness of the medium layer on the ray path between the areas dA_i and dA_j

4. Calculation of the fluxes to each of the surface and volume zones on the basis of the values obtained.

To obtain reliable results of heat flows to the pipes at each time in the furnace, it is necessary to determine as accurately as possible the parameters adopted in the model that affect heat transfer. Since the main source of heat in the furnace is the fuel burnt in the burners, special attention must be paid to the composition of the gas mixture formed in the combustion process. For natural gas combustion products are a mixture of carbon dioxide and water vapor (CO_2 + H_2O). These gases are the main radiating components of the furnace space atmosphere, and their high temperature and significant volume makes them one of the main radiation sources in the furnace as a whole. The key characteristic determining the degree of radiation of the furnace atmosphere is the absorption coefficient k, which can be obtained from the expression:

$$k\left(T, pCO_2, pH_2O\right) = \frac{1}{L}\left(1 - \epsilon\left(T, pCO_2, pH_2O\right)\right) \quad (5)$$

where ε is the integral emissivity of the considered volume of the gas mixture; *L* is the length of the characteristic path of the beam in a given volume.

Taking into account the strong dependence of the parameter ε on the composition of the gas mixture, the geometric configuration of the gas volume and gas temperature, its determination is associated with significant computational difficulties caused by a significant change in the temperatures and composition of the gas both at different points in the furnace space and at various times during the combustion of fuel. In this article, for the calculation by the zonal method, the determination of the absorption coefficient was carried out using the algorithm of exponential wide bands model (EWBM), which allowed achieving accuracy of results comparable in accuracy to the calculation of the FVM method.

3. Parameters and Modeling Object

As the object of modeling, a ring furnace of the pipe-rolling line No. 1 of OAO 'Seversky Pipe Plant' (Polevskoy) was chosen. The main design and operating parameters of the furnace are given in Table 1.

Table 1: Parameters of the ring furnace.

Average diameter	24 [m]
The length of the furnace along the middle line	70.7 [m]
Working width	5.2 [m]
Working space height	2.04 [m]
Diameter of the billet	290–360 [mm]
Length of the billet	2300–4500 [mm]
Weight	933–3596 [kg]
The number of billets in the furnace	122
The arrangement of billets	Single
Furnace output	Up to 90 [t/h]
Heating temperature	1200–1300 [°C]
Number of control zones	5 + 1
Number of burners	56
Heating air temperature	450–500
The maximum gas flow rate	5400 [m3/h]

The modelling of this furnace was caused by the installation of an improved design of the furnace bottom during the furnace annual repair. In accordance with the patent RU 128301 U1 'Device of the bottom of the heating furnace' (priority of 12.11.2012) [6] the bottom of the furnace, consisting in the installation of longitudinal protrusions 290 mm in width and 60 mm in height, spaced from each other at a distance of 350 mm, have been mounted (see Figure 1).

As a basic mode for simulation of heating with different design of the bottom, a characteristic mode with a furnace production was taken: 60 t/h (typical for the operation of the furnace in the rolling line). The criterion for obtaining satisfactory results of heating is that at the end of the heating the temperature of all parts of the billet is not lower than 1280°C ± 15°C

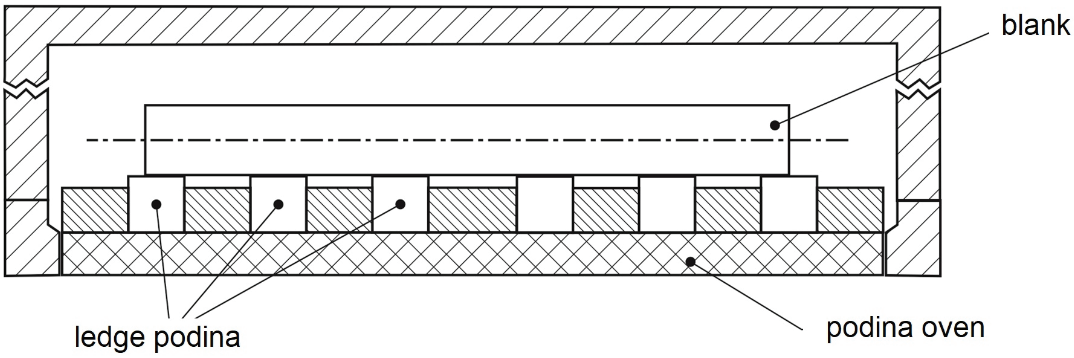

Figure 1: Cross-section of the furnace with an improved design of the bottom.

4. Comparison Results

The model of the furnace along the length was divided into 12 calculation areas. Each area includes 10 surface and 2 volume zones. Each billet has 5 surface zones, of which 4 zones correspond to the bottom, upper side, lower side, billet of the billet, respectively, and one zone simulates one or two end faces of the billet. Individual zones simulate the end faces of the furnace.

The result of modeling each of the temperatures of the surface of the zones is shown in Figure 2 for the FVM method and in Figure 3 for the zonal method:

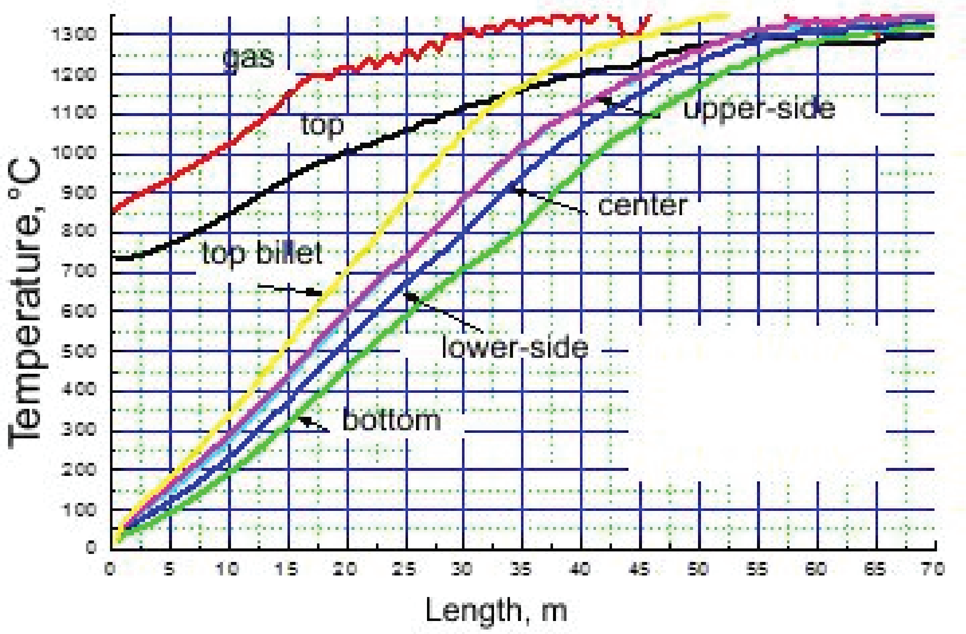

Figure 2: The dynamics of heating of various parts of the billet, calculated using the finite volume method (FVM).

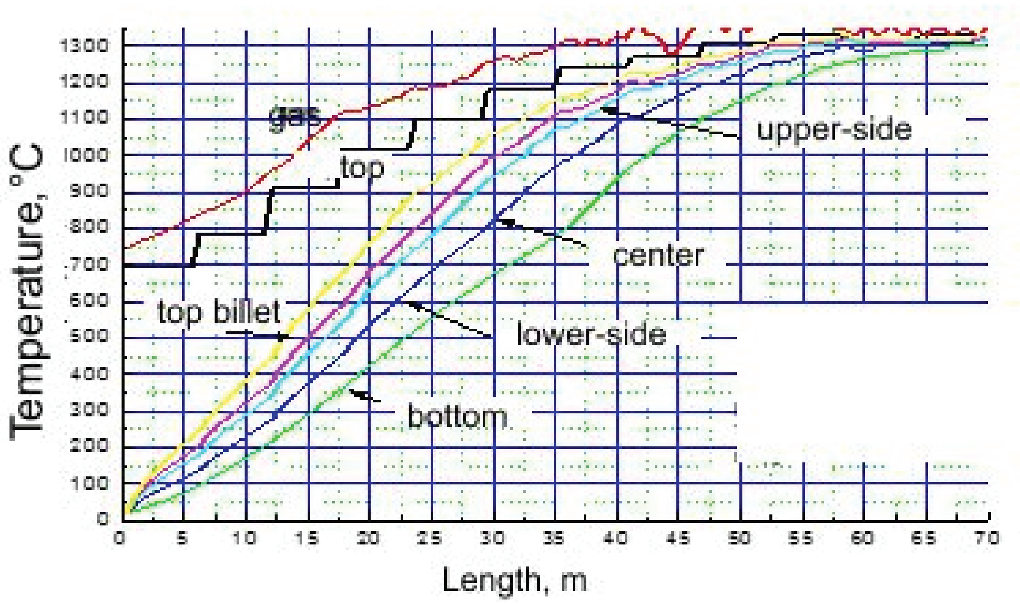

Figure 3: The dynamics of heating of various parts of the billet, calculated using the zonal method.

Comparison of the results of the two methods shows that the accuracy of calculations for both methods is comparable and is no more than 50°C (with the maximum discrepancy for the oven smoke temperature). A smaller breakdown of the cells in the FVM method makes it possible to obtain refined information on the temperature of the furnace zones (for example, for the zone of the furnace roof, which in the zonal method has a stepped nature due to the large size of the zones). Since the composition of the furnace atmosphere varies considerably depending on the furnace zone, a dynamic recalculation of the radiation absorption coefficient is required. It can be noted that with the dynamic calculation of the absorption coefficient for cells by the EWBM method, the total execution time of the FVM method exceeds the simulation time by the zonal method by 34s. If the dynamic calculation of the absorption coefficient is not used, the FVM simulation results do not correspond to the physical heating process and do not allow to obtain adequate data in the simulation.

5. Conclusions

In this article, two methods of mathematical modeling of heat exchange by radiation were analyzed: the finite volume method and the zonal method. The geometry of the selected modeling object was constructed a circular heating furnace with a rotating hearth for heating a continuously cast billet.

As a result of the simulation, the FVM and Zonal methods showed comparable modeling accuracy (the divergence does not exceed 50°C). The FVM simulation time exceeds the execution time of the zonal method by 13% due to the requirement to calculate the absorption coefficient for each of the allocated volumes.

References

[1] Modest, M. F. (2003). *Radiative Heat Transfer* (second edition). New York: Academic Press.

[2] Lockwood, F. C. and Shah, N. G. (1981). A new radiation solution method for incorporation in general combustion prediction procedures, *in Eighteenth Symposium on Combustion*, pp. 1405–1412. Pittsburgh: The Combustion Institute.

[3] Lisienko, V. G. (2008). *Improvement and Efficiency Energy Technologies and Industries (Integrated Energy-technological Analysis: Theory and Practice)*, 608c. M.: Teplotekhnik.

[4] Lisienko, V. G., Zhuravlev, A. Yu., and Kataev, B. I. (1973). Analysis of the local characteristics of external high temperature heat exchange in flame furnaces. *Izvestiya Vuzov. Iron and Steel*, no. 6, pp. 131–135.

[5] Malikov, G., Lisienko, V., Viskanta, R., et al. (2014). A new method for direct exchange area calculation in zonal method of radiant heat transfer modeling in combustion furnaces, in *IMECE2014-36983*, pp. 1–6.

[6] Toporov, V. A., Gubin, Yu., Shipunov, M. A., et al. Patent for useful model RU 128301 U1 Device bottom annular heating furnace (priority of 12.11.2012).