Light Metals 2014
Edited by: John Grandfield
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COMPUTATIONAL ANALYSIS OF THERMAL PROCESS OF A REGENERATIVE ALUMINUM MELTING FURNACE

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Keywords: Regenerative aluminum melting furnace, Thermal process, Numerical simulation

Abstract

To understand melting behavior of a regenerative aluminum melting furnace, a computational fluid dynamics based on process model was developed and integrated with user-developed melting model, oxide loss model, burner reversing and burning capacity model. Simulations of melting process were made to model the flow and thermal phenomena in such a furnace. The rules of thermal process on melting behavior are obtained: Aluminum temperature increases slowly with melting time in solid-liquid zone, but rises faster when leaving solid-liquid phase lines. Furnace temperature first increases with melting time, then stepwise decreases, lastly periodically increases. Oxide weight parabolically increases with melting time. Aluminum temperature parabolically increases with oxide thickness. In early melting stage, flue gas temperature reduces with liquid fraction, yet in later melting stage increases. Oxygen concentration in flue gas increases with liquid fraction in early melting stage yet remains constant in later melting stage.

Introduction

Aluminum products impact daily life for every community and person, particularly in transportation, container and packaging, and building construction industries because aluminum products have excellent mechanical properties, and are corrosion resistant material that can be repeatedly used. Aluminum melting is typically accomplished in large reverb, natural-gas-fired furnaces with capacities ranging up to 110 metric tons. Aluminum melting furnaces are key equipment in melting and casting industries. A large amount of energy may be consumed, which accounts for about 32% of total energy consumption during aluminum and aluminum alloy process procedure, yet more than 50% emissions are flowed out from the chimney [1]. In recent years, along with raised aluminum processing yield and demand of high quality for aluminum alloy castings in our country, high thermal efficiency, less pollutant emission and good product are demanded. Hence, it is important for both theories and practices to comprehensively understand thermal process of aluminum melting furnaces by numerical simulation, which will result in great improvement of energy-saving and optimization in aluminum melting furnaces.

In order to investigate how transfer phenomenon affects the efficiency of aluminum melting furnaces, scientists employed numerical simulation technologies to analyze heat and mass transfer phenomenon during melting process. The U. S. Department of Energy, Albany Research Center has completed a 4-year DOE program on "improving heating efficiency of aluminum melting furnaces" [2]. The results from some of the studies completed under this program have been successfully implemented at several of the plants with achieving substantial savings in natural gas usage. Nieckele et al discussed the flame pattern, temperature distribution, species concentration and flow field for aluminum melting furnaces from burner structure, the type of fuel and oxidant [3]. The behaviors showed the possible damages caused by the process if long or too intense and concentrated flames are present. In order to understand how flames/loads interaction affects furnace efficiency in aluminum melting furnaces, Ashwini et al presented the influence of loads at different stage of melting process [4].

In most of the previous studies, they did not consider molten aluminum in the furnace and neglected the interaction between combustion space and the aluminum bath. What's more, the thermal process was regarded as a steady state. In this way, steady-state solutions would not cease until the static heat balance has been obtained in the furnace, i.e., heat generation equals the heat loss. The problem is that, actually, in the melting furnace, the energy incomes and energy expenses cannot be balanced until the melt gets to a very high temperature (e.g. 1300K), which deviates from the melt temperature dramatically. Therefore, new calculation approach has to be carried out for performing more accurate prediction. In the present work, this paper concerns fuel combustion, heat transfer between combustion space and aluminum bath, phase change, oxide growth, burner reversing and varying of heating load, and heat loss through furnace walls. The most important innovation is that a transient solution scheme for thermal process of aluminum melting furnaces is adopted here. Thus, the corresponding results can represent the instantaneous situation, which is consistent to actual condition. The rules of thermal process on melting parameters are investigated, which may provide a theoretical guide for improving product quality, saving energy, lowering the cost and reducing emissions.

Physical model

Round-top reverb furnaces have become the principal furnace type used worldwide in the aluminum industry [5]. The most obvious advantage of these furnaces, as compared to stationary, rectangular-shaped side charged melters, is the speed of charging large volumes of scrap metal. In this study, the aluminum bath is situated beneath, and regenerative burners are installed laterally. In the upper part of the furnace, natural gas is mixed and burned with air. Meanwhile, in the lower part of the furnace solid aluminum is melted and liquid metal is heated. The produced liquid aluminum is tapped into a holding furnace, further refined and then directly transported to the industrial partner or cast into ingots. When aluminum melting furnaces work, No. 1 burner begins to ignite natural gas and No. 2 burner is used as the main flue. The reversing time between them is 60 seconds. 80% of high-temperature gases are exhausted through

the main flue, and the rest from the secondary flue. The flue gas leaving the furnace was rapidly cooled by a regenerative chamber, and then vented out through a chimney. The schematic diagram of the burner and the flues in the furnace is shown in Fig. 1.

Under the precondition of computational accuracy and reflection of main rules inside aluminum melting furnaces, in the present study, it is necessary to make several assumptions to simplify the physical model due to a complex melting process.

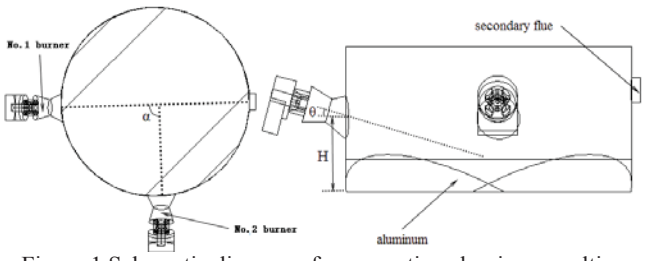

Figure 1 Schematic diagram of regenerative aluminum melting furnace

(1) Due to the melting process considerations, the liquid aluminum can be assumed to be stagnant. No stirring is assumed. Chemical reactions above the aluminum surface can be neglected. However, radiation and convection between combustion space and aluminum bath are taken into account.

(2) Aluminum surface is homogeneously covered by alumina. The initial thickness and the emissivity of oxide layer are 5*mm* and 0.33 respectively. Because the heat loss is minimal through furnace walls, the walls may be assumed to be adiabatic. The emissivity of the inner walls has little effects on melting process, thus, it is supposed to be 0.8.

(3) Liquid flow after solid melting is not included in the model. The latent heat in the solid-liquid zone is assumed to release linearly.

(4) To solve conveniently, it may be supposed that there is a stepwise relationship between burning capacity and liquid fraction. Here, the burning capacity is a correction coefficient of burner capacity.

Basic models

The conservative equations include mass, momentum, energy and chemical species equations. In addition, a turbulence model, combustion model and radiation model are also included. The widely used standard k-ε model was applied in most of the simulations in this study. At the solid surfaces, the non slip condition was enforced. However, in the region close to the wall, the standard wall functions have been used. All walls were considered as impermeable. Because of shell conduction, a model using user-developed oxide loss model is not coupled with a non-premixed combustion model. An eddy-dissipation model was utilized for the combustion of the natural gas with air. For thermal process in aluminum melting furnaces, heat transfer from the gas zone through the aluminum surface is the key for the thermal process and radiation plays the dominant role. Several radiation models were implemented in FLUENT, including P-1, Rosseland, Discrete Transfer Method, Discrete Ordinate and Surface-to-Surface. The P-1 model is valid for an optical thickness greater than 1, and in the present case, the optical thickness is estimated at 1.6. P-1 was chosen in most of the simulations because of its accuracy, robustness and less computing time compared with DTRM. For the P-1 model, the Weighted Sum of Gray Gases Model was used for the calculation of the absorption coefficient.

Fluid-solid coupled heat transfer model

By the principle known melting, the rise of aluminum temperature mainly depends on heat transfer between combustion space and aluminum bath, which was implemented by fluid-solid coupled model in the study. According to the assumption (1), in the current model, the aluminum bath was regarded as a conducting solid. Eq. (1) is used to describe heat transfer through the interface of fluid and solid.

$$\lambda \frac{\partial T}{\partial n}\Big|_w = h(T_f - T_w) + \varepsilon\sigma(T_f^4 - T_w^4) \qquad (1)$$

Where, λ is the thermal conductivity of the solid. h is the local convective heat transfer coefficient. T_f is the fluid temperature. T_w is the temperature of the coupled wall. ε is the solid emissivity. σ is the Stefan-Boltzmann constant.

Melting model

Thermal process of aluminum melting furnaces involves phase change of aluminum melting. Compared to usual heat conduction, an obvious characteristic of melting process is the release of latent heat. To deal with the latent heat term, the key is to obtain the relationship between liquid fraction and temperature. Release models of latent heat generally have linear scheme, quadratic scheme, lever rule and Scheil equation. However, for an aluminum alloy, the amount of latent heat is the same. They differ only in its release velocity. To solve conveniently, the equivalent-specific heat method is chosen to process the latent source item of phase change.

$$c(T) = \begin{cases} c_1(T) & T \le T_S \\ [c_1(T) + c_2(T)]/2 + L/(T_L - T_S) & T_S < T < T_L \\ c_2(T) & T \ge T_L \end{cases} \qquad (2)$$

Where, c_1 is the specific heat of the solid aluminum, c_2 is the specific heat of the liquid aluminum, T_S is the solidus temperature, T_L is the liquidus temperature, L is the latent heat.

Oxide loss model

Aluminum is a very reactive metal, thus oxidation is always occurring during its life. When heated to high temperature, aluminum is easy to react with micro-oxidation atmosphere. Because the main energy source of aluminum melting furnaces is usually supplied from flame heating, gas flow and combustion have significantly influence on oxide growth during melting process. In the present study, according to the oxidation kinetic and practical experiences, oxide loss model of aluminum melting furnaces was established under partial oxide scaling conditions, then the model was further revised based on actual factors. The oxide weight and thickness at different temperatures were calculated by the following Eq. (3):

$$\omega = \omega_0 + \sum_{i=1}^{\infty} A_i \delta \tau_i^{P_i}, \quad s = 1000 \times \frac{\omega}{\rho_{ox} g_{Al}} \qquad (3)$$

Where, ω_0 is initial oxide weight, s is oxide thickness, g_{Al} is aluminum content in oxide, ρ_{ox} is initial oxide density, ω is oxide weight, A_i and P_i are correction coefficient for temperature and micro-oxidation atmosphere respectively. Constants in above the literature were obtained by data fitting of the Al-Mg alloy.

Due to thin oxide thickness, its growth may be negligible for gas flow in the furnace. In this study, a shell conduction model was employed. By in-situ measurement, the oxide thickness is assumed to be constant, i.e., 5 *mm*. By taking into account the influence of oxide layer on thermal process of aluminum melting furnaces, the equivalent-thermal resistance method was used to tackle heat transfer between oxide layer and aluminum melt. The oxide weight also increases owing to oxide growth, thus the equivalent-mass method turned the growth of oxide thickness into oxide density change. The computational formula is shown in Eq. (4):

$$\lambda_{ca} = \frac{\lambda_{ox} \times \delta_{ox}}{s}, \quad \rho_{ca} = \frac{s \times \rho_{ox}}{\delta_{ox}} \qquad (4)$$

Where, λ_{ca} is equivalent-heat conductivity of oxide layer, λ_{ox} is initial heat conductivity of oxide layer, δ_{ox} is initial oxide thickness, ρ_{ca} is equivalent-density of oxide layer.

Burner reversing and burning capacity model

After solid aluminum is melted, the heat requirement of molten aluminum reduces substantially. To avoid overheating molten aluminum, burning capacity need be adjusted in industry production. In this study, according to the assumption (4), the change of burning capacity was implemented by a user-developed burner reversing and burning capacity model.

With the application of High Temperature Air Combustion in aluminum melting furnaces, regenerative burners work alternatively, thus, transient thermal process takes place in aluminum melting furnaces. The distribution of aluminum temperature is different from that under traditional burners. If thermal process of regenerative aluminum melting furnaces is counted as a steady state, alternatively heating aluminum through regenerative burners can not be embodied. In this paper, considering burner reversing, unsteady thermal process of regenerative aluminum melting furnaces is determined numerically by the solution of the conservation equations, via a finite volume technique, using the FLUENT program. In the case, the period of the burner reversing is 60 seconds.

Boundary conditions and independence analysis

The composition of natural gas is supposed to be standard. The initial temperature in the gas zone and the aluminum zone was set as 300 *K*. The inlet boundary conditions of air are mass flow (1.871 *kg/s*) and temperature (823 *K*). And the inlet boundary conditions of natural gas are velocity (43.195 *m/s*) and temperature (300 *K*). These values were obtained according to relevant mass flow rates of air-fuel mixture by heat balance test from a company. Outflow boundaries were set for the outlet, and the weight of the main flue and the secondary flue is 0.8 and 0.2 respectively. Boundary turbulent parameters are given by κ=0.5χu^2 and ε=2.5$c_\mu^{0.75}\kappa^{1.5}l^{-1}$, where κ is the turbulent kinetic energy, m^2/s^2; ε is the turbulent kinetic energy dissipation rate, m^2/s^3; u is the superficial velocity, m/s; c_μ is the empirical constant, 0.09; χ is the inlet turbulence intensity and l is the inlet turbulence scale, m. On the inner walls surrounding the combustion space, non-slip momentum condition was enforced. Actual walls here were represented by the shell conduction model supplied by FLUENT, and heat transfer between the outer sides of the 'shells' and the ambient was designated to be convection.

In this case, multi-block unstructured grid was employed. Finer meshes were used in some sensitive areas, e.g. burner and flame areas, while coarser meshes were applied in the lower part of the furnace. Generally, if the grid spacing is too large, it increases the truncation error. Thus, the simulation results may be distorted. In contrast, it greatly increases the amount of computation if a small grid size is selected. A finer mesh could have resolved the melting process more precisely. However, this was considered unnecessary at this stage to cut down on the computational time needed. By adjusting the grid size slightly, the dependence of numerical solutions on these small changes can be observed. If the coarse mesh gives a solution which is invariant with the finer meshes, the grid independence is said to be achieved. The time-step independence test is similar and is intended to ensure that time steps in simulation are as large as possible to reduce computation time while being sufficiently small to provide accurate solutions. If the time step in an unsteady flow problem is increased significantly, numerical solutions lose accuracy because information details are lost between time steps. To ensure solutions are independent of time step, care should be taken to retain an adequate amount of flow information by decreasing time step, while decreasing computational time by increasing time step. However, the solution may become meaningless if too large a time step is taken due to large truncation errors. This initial time step was estimated according to the characteristic velocity for the problem considered here and the size of the grid cell. As a result, in considering both the numerical accuracy and computational expenses, the optimum grid and time step are 377,442 elements and 1 second for the computation, respectively.

Implementation of program

Based on basic models, the hybrid programming method of FULENT UDF and FLUENT Scheme was used to develop user-defined melting model, oxide loss model, burner reversing and burning capacity model which are integrated into the CFD framework. Basic models and user-defined models with the exchange of melting information by fluid-solid coupled heat transfer model to accomplish numerical simulation of thermal process of regenerative aluminum melting furnaces. Basic models include basic conservation equations, *k-ε* turbulence model, P-1 radiation model, and Eddy-dissipation combustion model. Coupled relationships between basic models and user-defined models are shown as follows: Burner reversing and burning capacity model provides necessary solution parameters and boundary conditions for basic models, such as time-step, natural gas mass flow and air velocity. In order to obtain varying burning capacity, burner reversing and burning capacity model achieves liquid fraction from the melting model. By swapping aluminum

temperature and liquid fraction among melting model and basic models, aluminum melting is realized. According to aluminum temperature and air-fuel ratio in basic models, oxide weight and thickness are computed by oxide loss model. The solution procedure of FLUENT is shown in Fig. 2, and its explanations are given below:

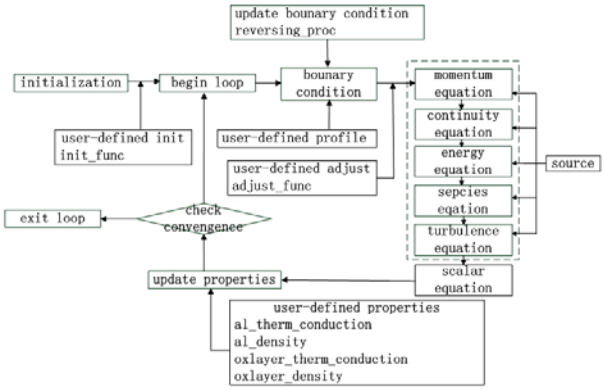

Figure 2 Solution procedure of FLUENT for regenerative aluminum melting furnace

The oxide layer is initialized by *init_function* function. The liquid fraction, oxide weight and thickness are computed by *adjust_func* function. The oxide growth is implemented by *oxlayer_therm_conduction* and *oxlayer_density* function. The physical properties of aluminum are modified by *al_therm_conduction* and *al_density* function. The change of the burning capacity and burner reversing are implemented and the results are written to the file by *reversing_proc* procedure. If aluminum temperature reaches to 1013K by electromagnetic stirring, *adjust_func* function sends exit signal to *reversing_proc* procedure so that the program saves result and exits FLUENT.

To perform numerical simulation of thermal process of regenerative aluminum melting furnaces, unstructured grid using finite volume method is the basis for discretization of governing equations. Segregated solution with first order implicit scheme for time integration is used to solve governing equations, that is to say, continuity equation, momentum equation, energy equation, species equation and k-ε equation is orderly solved. Radiation model and combustion model are regarded as source term for energy equation and species equation respectively. First-order upwind difference scheme was employed. The SIMPLE algorithm is used to handle pressure-velocity coupling. The system of algebraic equation related to the mass conservation and chemical species conservation were solved by the "Addition Correction Multi-grid". All remaining conservation equations were solved by the TDMA line algorithm, with the block correction to speed convergence. The convergence criterion adopted was that the normalized residue for each of the conservation equations should be smaller than 0.001.

CFD Model validation

Efforts have been made to thoroughly validate the CFD model to ensure the accuracy of the simulations. Measurement data in 35 tons regenerative aluminum melting furnace in a company are carried out. The flue gas composition and temperature measured by thermocouples and flue gas analyzer are compared with computational results. The comparison of their results is shown in Table 1. Table 1 illustrates that numerical results are basically in good agreement with the experimental results. The comparison of temperature between computational data and measured data in combustion space and aluminum bath is shown in Fig. 3. The trend of simulation results is in accordance with that of measured data, and relative error is less than 5%, suggesting that the computational models were proved to be reliable and accurate.

Table 1 Comparison of simulation results and test values for an aluminum melting furnace

Item	Test	Simulation	Relative error/%
Melting time/*h*	5.1	4.8	5.88
CO_2/%	3.12	3	3.85
H_2O/%	5.97	5.75	3.67
N_2/%	76.53	76.68	0.20
O_2/%	14.34	14.53	1.32
NO_x/*ppm*	400	415	3.75
Pressure/*Pa*	18	16.51	8.28
Aluminum temperature/*K*	1021	1035	1.37
Furnace temperature/*K*	1280	1337	4.35

However, the calculated results are little higher than the measured results, which is mainly due to the opening of the door during the test. As cold air is absorbed into the combustion space under the negative pressure, the whole temperature in the furnace decreases. Besides, the heat loss through the furnace walls is neglected according to the assumption (2), which makes the simulation results increase. In a word, good correlation between the results obtained from the numerical simulation and from an experimental furnace tests demonstrate that CFD software FLUENT, in conjunction with user-defined models, is expected to be a useful tool because the physical behavior of melting phenomena in industrial furnaces can be explored, and can be applied in the study of the influence of thermal process on melting parameters of aluminum melting furnaces.

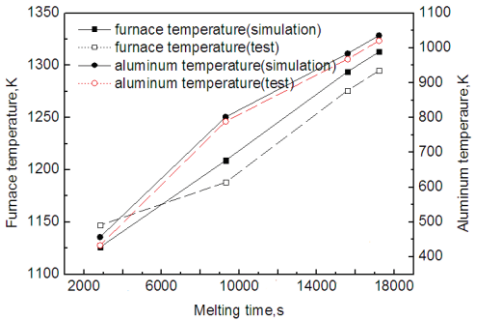

Figure 3 Comparison of temperature between computational data and test data in combustion space and aluminum bath

Simulation process analyses of regenerative aluminum melting furnace

In the light of No. 7075 aluminum alloy, thermal process of a regenerative aluminum melting furnace is simulated. Fig. 4 illustrates the relationship between melting parameters and melting time. After the liquid fraction reaches to point B, the aluminum temperature increases slowly with the melting time when phase change of partial aluminum occurs and burning capacity decreases, but rises faster when leaving solid-liquid phase lines. The liquid fraction increases linearly with the melting

time, and it is consistent with the release model of the latent heat in solid-liquid zone. One of the main purposes of the simulation is to obtain the total melting time under a certain condition. The liquid fraction curve can be regarded as the main criterion for the melting process, which indicates the time the aluminum starts to melt and the time it has been melted completely. For melting of about 35 tons aluminum, the total melting time is about 5.4 hours in this case. Because burners work alternately, the furnace temperature firstly periodically increases with melting time, then stepwise reduces due to the decrease of burning capacity, lastly periodically increases again when the burning capacity decreases to 30%. The heat flux through the aluminum face firstly increases with the melting time for quick rise of the furnace temperature. When aluminum starts to melt, the heat flux reaches an equilibrium state because the thermal conductivity of liquid aluminum is 1/4-1/3 that of solid aluminum. However, then, the heat flux linearly decreases when the liquid fraction ranges from 5% to 50%, then decreases slowly again. The RSD (relative standard deviation) of furnace temperature firstly periodically decreases with the melting time. In the range when burning capacity changes, the RSD of furnace temperature increases stepwise due to stepwise decrease of the high temperature zone. When the burning capacity stabilizes at 30%, the RSD of furnace temperature again decreases periodically. From the above-mentioned analysis, the burning capacity dominantly affects the thermal process of the furnace. The RSD of aluminum temperature firstly increases, then decreases when phase change occurs, namely, the liquid fraction reaches the value of A. Nonetheless, on the one hand, the temperature of upper aluminum in the aluminum bath exceeds melting temperature and rises quickly, on the other hand, bottom aluminum is still not melted, which leads to be great difference in temperature between the upper aluminum and the bottom aluminum. Therefore, the RSD of aluminum temperature increases again when the liquid fraction reaches the value of B (as shown in Fig. 4a).

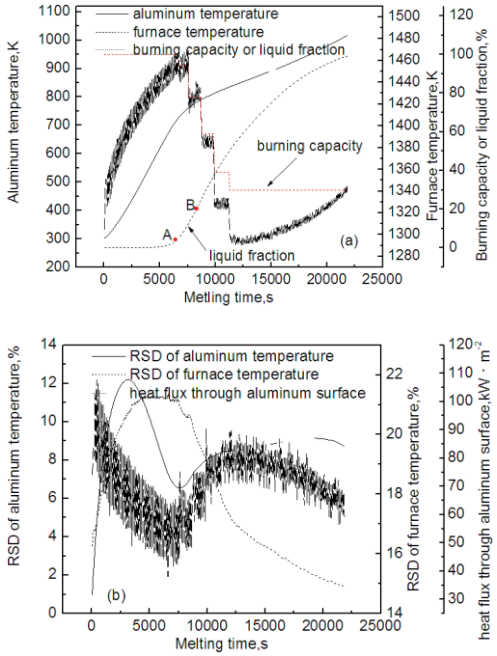

Figure 4 Relationship between melting parameters and melting time: (a) change curves of aluminum temperature, furnace temperature and liquid fraction or burning capacity with melting time; (b) change curves of RSD of aluminum temperature, and furnace temperature and heat flux through aluminum surface with melting time

Fig. 5 shows the oxide weight increases parabolically with the melting time. When aluminum loads start to be melt, the heat flux through the aluminum surface increases rapidly. Therefore, the aluminum temperature also rises quickly, and the oxide weight increases fast. The heat flux through the aluminum surface firstly increases with the oxide thickness, then decreases. The reason behind this is phase change and physical properties change of aluminum during melting process. The aluminum temperature increases parabolically with the oxide thickness. When the liquid fraction reaches to B point (Fig. 4a), the inflection point of the aluminum temperature appears corresponding to that of heat flux through aluminum surface. After phase change most of the aluminum occurs and the burning capacity decreases, the slowdown of the increase of aluminum temperature appears.

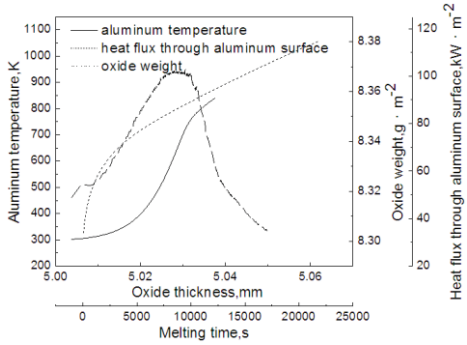

Figure 5 Influence of oxide layer on melting process

Temperature contours in the furnace for the different melting periods are shown in Fig. 6. From Fig. 6, after natural gas mixed with air starts to burn in the burner, the gases slope into the furnace and sink slightly, then, exhaust gas sweeps the aluminum surface. While flue gas reaches to furnace walls, the direction of gas flow changes. Thus, a large eddy appears in the gas zone, making some high-temperature gas in the furnace circulate. The recirculation helps accelerate the process of mixing of fuel and combustion air. Therefore, the residence time of high-temperature gas is prolonged. The disturbances of the combustion gas in the furnace are intensified, which promotes heat transfer between combustion gas and aluminum load. It increases furnace temperature and reduces melting time. From Fig. 6, high temperature and high velocity locate in the center of the aluminum surface. It is the reason that high-temperature gases at the center of aluminum surface have more intense heat transfer. Because of the round shape and vertical arrangement between the burner and main flue, high temperature and high velocity above the aluminum surface slightly shifts to the main flue. According to assumption (1), the significant heat transfer mechanism is thermal conduction in aluminum bath, so the temperature in the aluminum longitudinal section shows parabolic distribution in general. When single burner works, the flame comes into contact with the aluminum surface, which easily makes temperature distribution be non-uniform on the aluminum loads. However, on the one hand, the horizontal angle between burners is 90°, on the other hand, aluminum load is alternatively heated by regenerative burners, and the reversing time is very short. All these result in a decrease of the RSD of aluminum temperature. Besides, it is indicated that the secondary flue may control both temperature and pressure.

Consequently, if pressure is too high or too low, correct pressure can be achieved by the adjustment of a mechanical damper embedded in the flue system.

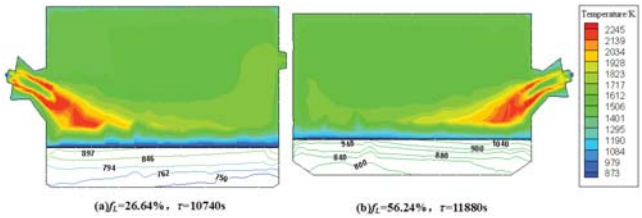

Figure 6 Temperature contours in aluminum melting furnace for different melting period

Change curves of flue gas temperature and oxygen concentration in flue gas with liquid fraction are shown in Fig. 7. By observing Fig. 7, the temperature of the secondary flue is higher than that of the main flue. It is related to be structure of the furnace. From Fig. 1, the horizontal angle between the burner and secondary flue is 180°, yet the horizontal angle between the burner and main flue is 90°, which makes high-temperature gas directly discharge from the secondary flue. According to assumption (4), in the early melting stage, the burning capacity decreases stepwise with the liquid fraction, yet in the later melting stage the burning capacity remains constant. So the flue gas temperature decreases with the liquid fraction, and increases again in the later melting stage. The oxygen concentration in the flue gas increases with the liquid fraction in the early melting stage, nevertheless, remains constant in later melting stage. The mass fraction of CO and O_2 in the flue gas is 0 and less than 3% respectively. Therefore, micro-oxidation atmosphere is gained and natural gas is burned completely with air.

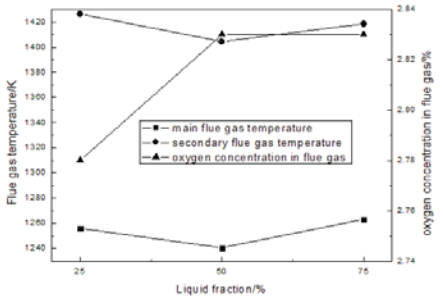

Figure 7 Change curves of flue gas temperature and oxygen concentration in flue gas with liquid fraction

The relationship between the wall temperature and melting time is presented in Fig. 8. The wall temperature of the furnace floor is much larger than that of the furnace roof and furnace side, which is related to a solid base and physical properties of furnace linings. According to assumption (4) and Fig. 4a, increasing the liquid fraction beyond 5%, the burning capacity starts to reduce stepwise with the liquid fraction. It leads to furnace temperature decrease. Therefore, the wall temperature rises slowly. While the burning capacity drops to 30%, the wall temperature again increases linearly.

Conclusions

The hybrid programming method was used to establish and simulate thermal process of the furnace. The reliability of the mathematical model was experimentally verified with heat balance test of the furnace. The rules of thermal process on melting parameters are achieved as follows:

(1) Aluminum temperature first rises quickly with melting time, and then rises at a slower rate. Furnace temperature first increases, then stepwise decreases, and lastly increases. Heat flux through the aluminum surface first increases with melting time, then decreases. RSD of furnace temperature first decreases, and then increases, lastly decreases again. RSD of aluminum temperature first increases with melting time, then decreases, finally increases again.

(2) Oxide weight parabolically increases with melting time. Heat flux through aluminum surface firstly increases with oxide thickness, then decreases. Aluminum temperature parabolically increases with oxide thickness. The inflection point of aluminum temperature appears corresponding to that of heat flux through aluminum surface.

(3) In the early melting stage, flue gas temperature decreases with liquid fraction, yet increases in the later melting stage. Oxygen concentration in flue gas increases with liquid fraction in the early melting stage then remains constant in the later melting stage.

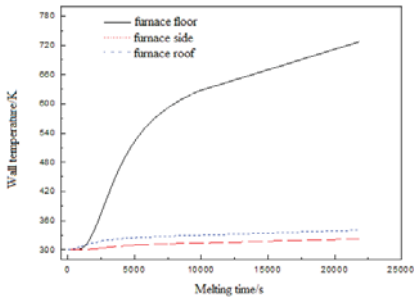

Figure 8 Relationship between wall temperature and melting time

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