The Structural Design and Analysis of Melting Aluminium Furnace for Flue Gas Circulation

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Abstract: ***It is the common problem for the intense energy dissipation of melting aluminium furnace. It is the biggest heat waste in ordinary combustion to discharge the flue gas to the atmosphere. Therefore, to design a new type of external device for melting aluminum furnace, will cycle the flue gas back to the melting aluminum furnace to participate in the combustion, and reuse the heat energy. In the condition of the absence of heat balance test, the smelting process is divided into several time node, using MATLAB software to heat balance calculation by iteration, so that it is getting the fuel consumption. In the result, it shows that compared with ordinary combustion, using this way can save fuel by 43.6%, and its combustion efficiency is 38.57%,and can maintain the stability of temperature of the furnace. The structure of the device and the calculation method of energy savings can be utilizedto reference in the research and the designersin enterprise.***

Keywords: melting aluminum furnace, flue gas circulation, to save fuel, heat balance calculation

1. Introduction

Melting aluminium furnace is the main equipment in the process of smelting aluminum, it is used to melt aluminum, to make its quality uniform and meet the requirement of the chemical composition, which is in order to cast and provide qualified liquid aluminum for other processes. The energy consumption of the melting aluminium furnace accounts for about more than 40% of the total energy consumption in the aluminum processing plant [1-2]. As a result, it has a great of significance to improve the level of combustion technology of melting aluminium furnace to reduce the energy consumption of aluminum processing for the improvement of enterprise economic benefit and the national strategy of energy conservation and emissions reduction.

The melting aluminium furnace in the early is installed with the air heat exchanger on the flue pipe to recover the heat of flue gas that took away, and it preheats the combustion-supporting air to a certain temperature to participate in the combustion. According to the thermal principle of industrial furnace, as improving the temperature of each combustion-supporting air 100 ℃, the fuel can be saved about 5%, or the temperature reduction of flue gas is about 100 ℃, the flue can be saved by 5.5%, but after transferring the heat，the temperature of the emission gas is still above 500℃.After the energy crisis of the 1970s, regenerative combustion technology on reheating furnace had got the development by leaps and bounds. It includes two basic technical measures: one is to use the device of regenerative heat exchange that the temperature efficiency is as high as 95%, and the thermal recovery is more than 80%,to the maximum limit to recovery of sensible heat of high temperature flue gas, which is used to obtain high temperature combustion air or gas and make the extreme heat recovery. Another one , due to the high temperature combustion air or gas that enters into the furnace, and takes the graded way to burn fuel grade and the combustion products in furnace is in the entrainment of the high-speed air and to dilute the concentration of the oxygen volume in the reaction zone, get a concentration of 2% - 15% of low oxygen combustion, achieve the low emissions of NOx, but its frequent commutation can cause fluctuation of the furnace temperature and furnace pressure, commutation combustion in the instant is discontinuous, and in the meantime there is also a burner obstruction, coking, detonating, explosion, gas problem, short circuit and so on. Oxygen-enriched combustion technology is that the mixed gases of O_2 and CO_2 is in the instead of air entering into the furnace as fuel, which is mixed with fuel to burn, in the oxygen-enriched combustion, the concentration of CO_2 is as high as 90% above, and don't need to separate and will most directly liquefy $CO_2$from flue gas.It is an effective way to decrease carbon dioxide emissions. L. Frank, Bloom engineering company, comparing three kinds of combustion technology of cold air and fuel, oxygen-enriched combustion and regenerative combustion, analysing the application of the cost for three kinds of combustion technology and the impact on the furnace combustion efficiency, pointing out that in melting aluminium furnace the use of oxygen-enriched combustion technology can also achieve the effect of reducing energy consumption, but he is not on the in-depth research.

In this article, therefore, to design an external device of melting aluminium furnace, which contains a variety of characteristics of combustion technology, the flue gas will loop back to the melting aluminium furnace to take part in combustion. It put forward the suitable calculation method of flue gas cycle of melting aluminium furnace before the test, based on the conventional combustion in the boiler thermodynamic calculation formulas, combining with the characteristics of flue gas circulating combustion technology of thermal system. A result of heat balance calculation shows that the temperature of the furnace is uniformity and stability and can achieve the goal of energy saving. Providing the necessary theoretical basis for development and improvement of the flue gas circulation and energy saving calculation in the future, in the meantime the air is completely replaced by the flue gas circulation, so the combustion products will no longer produce NOx compounds.

2. Principle of Circulation Combustion of Flue Gas

The technology of circulation combustion of flue gas is another type of combustion technology that consisted of several frontier combustion technologies. Fig.1 is the schematic diagram of a thermodynamic system of the flue gas circulation combustion. In the beginning fuel burns with the inlet air induced by ventilator, then the oven door is closing slowly, flue gas after burning will be out of the chamber of a stove or furnace outlet pipes. when the flue gas in the pipe can be divided into two parts, part one discharges, another part recycles by pipelines, the cycle of flue gas will be mixed with added oxygen, which become the composition mixture, the oxygen flow and fuel flow is equivalent by the ratio of chemical reaction, and furtherly mixed by the ventilator, the ventilator at this time is no longer sucked in air, in the meantime the mixture of cycle gas and fuel is burning in the chamber entrance.

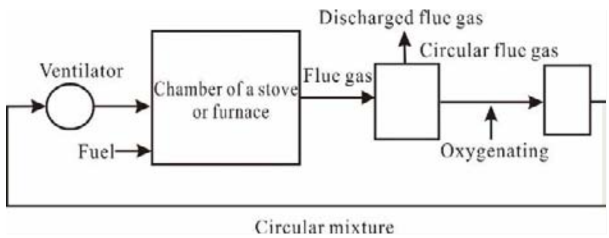

Figure 1: The diagram of thermal system of flue gas circulation combustion

3. Device Design

In this paper, the device design of flue gas circulation of melting aluminium furnace is shown in Fig.2.

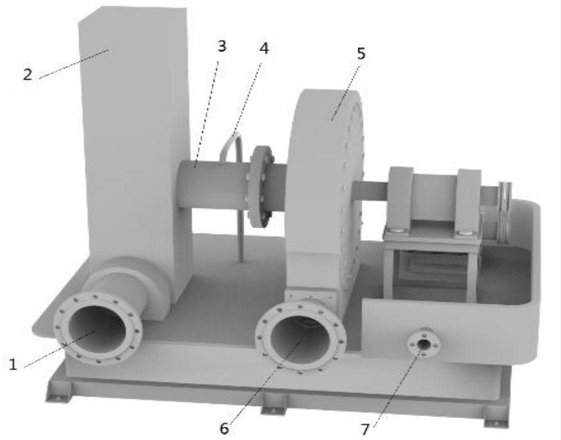

Figure 2: The external device of flue gas circulation
1. Furnace outlet pipe 2. Emission chimney 3. The pipe of flue gas circulation 4. Oxygenating pipe 5. Ventilator 6. Furnace inlet pipe 7. Fuel pipeline

The working process for the external device of flue gas circulation: the flue gas enters the pipeline, and the flue gas flows upwardly through the circulating pipeline of flue gas by its own kinetic energy and heat energy, the other part continues to flow in the discharge of chimney until discharge into the atmosphere. Oxygen from the pipe flows into the circulation pipe of flue gas, the flue gas with oxygen flows into the ventilator, and that is mixed by ventilator uniformly, which comefrom the furnace inlet pipe is burning in the hearth.

4. Heat Balance Calculation

The analysis method of heat balance is based on the first law of thermodynamics, suggesting the quantity relationship between conversion and the process of energy transfer, and it is based on the heat balance calculation of melting aluminium furnace that the maximum fuel consumption of the furnace can be calculated (or maximum heat consumption), the heat balance refers to input the balance between the heat of the furnace and heat output, namely the income items and hot spending items.

Thermal equilibrium equation is as follows:

$$Q_1 + Q_2 = Q_3 + Q_4 + Q_5 + Q_6 + Q_7 \quad (1)$$

Q_1 - Chemical combustion heat of Methane,kJ;

Q_2 - Physical heat of recycling mixture, kJ;

Q_3 - Thermal dissociation loss, kJ;

Q_4 - Absorption heat of furnace wall, kJ;

Q_5 - Absorption heat of oven door, kJ;

Q_6 - Absorption heat of Aluminum material, kJ;

Q_7 - Heat of flue gas taken away, kJ;

4.1 Heat Income Items

4.1.1 Chemical combustion heat of methane:

Chemical combustion heat of methane means that all chemical heat produced by methane consumption per hour of the melting aluminium. This article assumes that the input of methane combustion has completely produced heat Q_1.

$$Q_1 = BQ_d \quad (2)$$

B -Methane consumption， $\mathrm{N \cdot m^3 (kg/h)}$;

Q_d -Methane calorific value in low， $\mathrm{kJ / N \cdot m^3 (kg)}$;

4.1.2 Physical heat of circulation mixture

In circulation phase, the added oxygen that is equivalent to the methane is consisting of a new mixture of flue gas .The physical heat of the mixture in melting aluminium furnace is

Q_2.

$$Q_2 = B_1 c_t \left(t_k - t_0\right) \quad (3)$$

B_1 -Circular mixture flow, $N \cdot m^3 (kg/h)$;

c_t -Specific heat of the circular mixture, $kJ/\left(N \cdot m^3 \cdot ℃\right)$;

t_k -Temperature of the cyclic mixture, ℃;

t_0 -The air temperature, ℃;

4.2 Heat spending items

4.2.1 The heat loss of thermal dissociation:
Under the operating temperature and pressure of general industrial furnace, it is usually only considered thethermal dissociation reaction between Co_2 and H_2O

$$Q_3 = 12623.6 f_{CO_2} V_{CO_2} + 10784.4 f_{H_2O} V_{H_2O} \quad (4)$$

f_{CO_2} -Dissociation degree of CO_2;

f_{H_2O} -Dissociation degree of H_2O;

V_{CO_2} -Carbon dioxide volume, m^3;

V_{H_2O} -Volume of water vapor, m^3;

4.2.2 Absorption heat of the furnace wall and the furnace door:

$$Q_4 / Q_5 = 3.6 \Sigma A \cdot q \quad (5)$$

A -Including the calculating area of the furnace wall, roof, bottom and the door, m^2;

q -The heat loss of furnace wall per unit area, W/m^2;

The furnace wall uses refractory clay bricks, its thickness is 0.232 m, thermal conductivity is $\lambda = 1.16 W/(m \cdot ℃)$, Specific heat capacity is $c = 963 J/(kg \cdot ℃)$, thedensity is $\rho = 2070 kg/m^3$, Thermal diffusivity is $a = \frac{\lambda}{c\rho} = 5.819 \times 10^{-2} m^2/s$, the temperature of the initial furnace wall is 0℃, the exteriortemperature of the furnace wall rises to 1100 ℃ in the heating rate of $250℃/h$ and then keep warm, the calculation of the q refers to [6].

4.2.3 Absorption heat of aluminum material:
For convenient calculation, approximatively regard the heated area of aluminum material as a plane. In the melting aluminium furnace, the heat of furnace gas radiation to oven door and aluminum materials is as follow.

$$Q_6 = \sigma \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4 \right] \varphi A_1 \quad (6)$$

σ -Export coefficient of radiation, $W/(m^2 \cdot ℃^4)$;

T_1、T_2 -The temperature of heat transfer on both sides, ℃;

φ -Radiation Angle coefficient of the material surface on the furnace wall;

A_1 -Heating area, m^2;

Q_7 can be calculated through the heat balance equation (1).

4 Program design of heat balance calculation

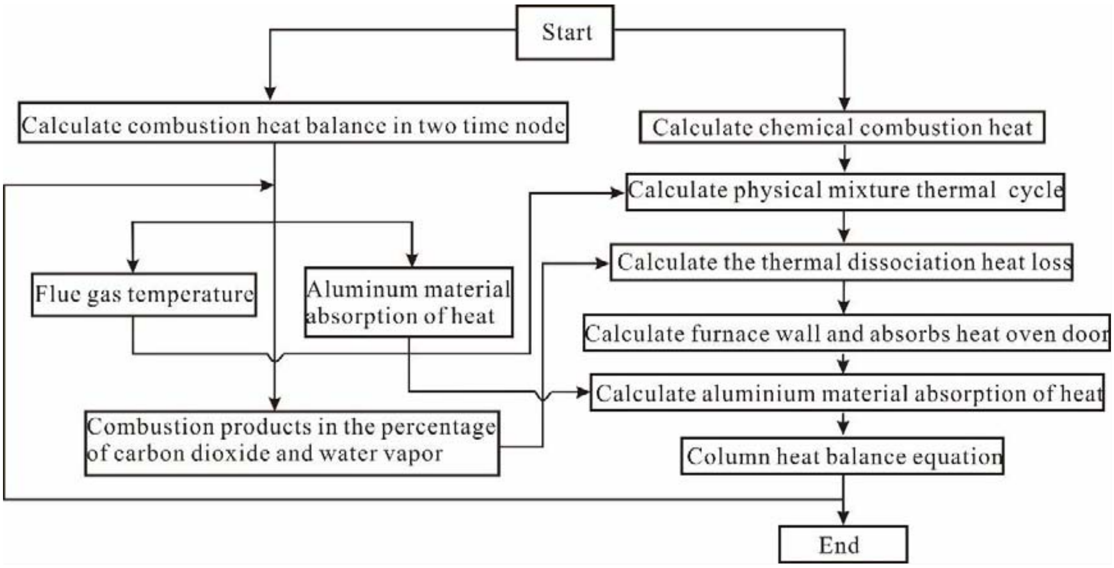

Figure 3: Program flow chart

5. Program Design of Heat Balance Calculation

When to design the melting aluminium furnace, it is unable that the thermal equilibrium experiment was carried out sometimes. But there was a need to the fuel consumption in the design. The flue gas heat and other data, and the traditional method is to use the heat balance estimate or budget, and the estimate can be according to the fuel properties, combustion modes, the experience data values, regarding the aluminum melting process as a whole. The downside of this approach is that the estimate can make calculation inaccurate, and it cannot reflect the process of heat change in the furnace. In this paper, the whole process of smelting method is to be divided into several time nodes, to calculate the heat balance between two nodes, and a time node before the results of calculated heat balance at the next time initial condition of iterative calculation. When the calculation for the entire process is expected to be completed, the accumulative time nodes are the time of melting aluminium furnace for smelting aluminium material. Because the heat balance is more tedious and manual calculation, so this paper takes calculation program written by MATLAB software, the application process is indicated in Fig.3.

6. Calculation Example and Analysis of Result

The datum condition: in this paper, the spatial structure is as showed in Table 1, the flow of methane is 100m3/h, the chosen ventilator is as showed in Table 2, the time between nodes of time step is 180 s.

Table 1: Sizes of furnace structure

Project	*Value*
High × Wide× Deep /m	1×2.85×1
Furnacespace /m3	2.85
Furnace area /m2	13.4

Table 2: Ventilator specifications

	Wind pressure/Pa	*Air volume/m3/h*
20℃	13000	1040
800℃	3900	1040

Through listing the equations of thermal balance each time nodes, it can be obtained by the absorbed heat of aluminum materials in each time nodes. The melting of aluminum material is 10 t. The aluminum smelting consumes heat which is consists of three parts: First, the heat which makes the temperature change form initial value to the melting point; Second, the required heat which change the aluminum states from the melting the solid aluminum to the same temperature of liquid aluminum; Third, the required heat which can make the temperature grow from melting point value to tapping temperature. When the above three parts are finished, the time node will be terminated. The heat balance results of ordinary combustion and flue gas circulating combustion, as shown in Table 3 and Table 4.

As shown in Table 3 and Table 4, most of the heat income comes from the combustion. Ordinary combustion accounts for 100% of the total heat income, in the Table 3. However, flue gas circulation combustion accounts for 85% of the total heat income, in the Table 4. Heat loss of flue gas in ordinary combustion accounts for 49.08% of total loss. From the heat balance calculation, according to the data from ordinary combustion emissions flue gas that temperature is between 1002-1028 ℃, so a large number of heat have been gone along with flue gas[9]. In the process of flue gas circulating combustion, flue gas loss accounts for 38.28% of the total expenditure, but most of it changes into the cycle mixture physical heat of the heat income, which accounts for 14.65% of the total heat income. The heat loss of flue gas is the difference value between the heat loss of flue gas and the physical heat of circulating gas, which accounts for 23.6%.

Thermal efficiency is an important index for the energy utilization level of furnaces [8]. The thermal efficiency of melting aluminium furnace can be expressed as follow:

$$\eta = \frac{Q_6}{\sum Q} \times 100\% \quad (7)$$

According to the results of the heat balance calculation, we can get the thermal efficiency ofordinary combustion is 28.37%, and the thermal efficiency of flue gas circulation combustion is 38.57%.

Table 3: Heat balance of ordinary combustion

Heat income			Heat spending		
Project	Heat MJ/furnace	%	Project	Heat MJ/furnace	%
Chemical combustion heat	39397.6	100	Thermal dissociation loss	2609.2	6.62
			Absorbed heat of furnace wall and furnace door	6275.94	15.93
			Absorbed Heat of aluminum material	11176.701	28.37
			The heat loss of flue gas	19335.759	49.08
Total	39397.6	100	Total	39397.6	100

Table 4: Heat balance of flue gas circulation combustion

Heat income			Heat spending		
Project	Heat MJ/furnace	%	Project	Heat MJ/furnace	%
Chemical combustion heat	22205.92	85	Thermal dissociation loss	1476.757	5.65
The physical heat of circular mixture	3827.021	14.65	Absorbed heat furnace wall and furnace door to	3537.348	13.54
Error	91.749	0.35	Absorbed heat of aluminum material	11111.046	42.53
			The heat loss of flue gas	9999.539	38.28
Total	26124.69	100	Total	26124.69	100

As is shown inFig.4, under the same condition using ordinary combustion and flue gas circulation combustion respectively, in each nodes the absorbed heat of flue gas for the circulation combustion of aluminum material were higher than the ordinary combustion, and on the melting time, time nodes number is 220 for ordinary combustion, time node number is 124 times for circulation combustion of flue gas, and the time of each time node is 180 s, so the further calculation for ordinary combustion time is 11 h, and the circulation combustion is 6.2 h, saving fuel by 43.6%. Aluminum material to absorb heat at the beginning of the circulation combustion of flue gas has a bigger change, because in the beginning it is caused that the flue gas of the ordinary combustion makes the furnace inlet unstable.

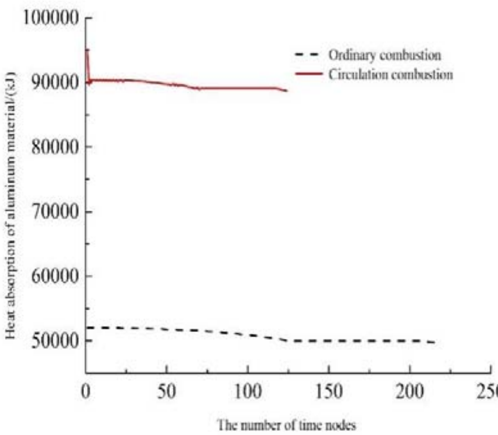

Figure 4: Two ways of absorbed heat of aluminum material for circulation combustion

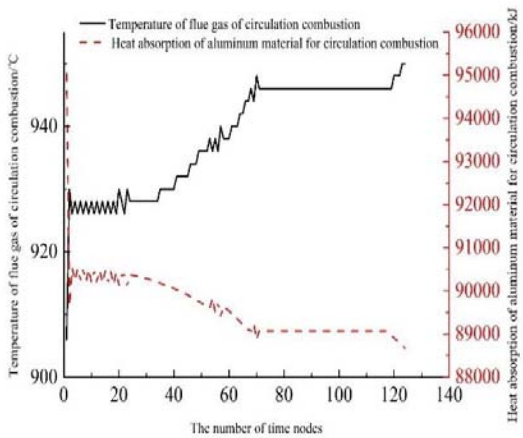

Figure 5: Absorbed heat of aluminum material and the flue gas temperature along with the change of time nodes

As shown in Fig.5, the temperature of flue gas at the time of the initial period of the node number has great changes, and then as number of time node increases, it has a slow, steady growth trend. The majority temperature of flue gas kept at 926-950 ℃, and its fluctuating is small, because the flue gas temperature indirectly reflects the status of furnace temperature. As a result it can keep a stable temperature.

The heat absorption of aluminum material is on the contrary, by contrast, and the curve of heat absorption of aluminum material and temperature of circular flue gas is symmetric distribution, this is due to the thermal income in items not only increase the cycle heat of physical mixture, but also according to the paper [10], the higher supporting-combustion gas is, the higher temperature of combustion is improving, and so does the heat. According to the principle of heat balance, the heat absorption of aluminium material will reduce. So advocating "more times" way of smelting, each time the capacity of aluminium is lower, and make each group heat absorption rate of aluminum melting remained at efficient stage, then put in another new batch of aluminum material.

7. The Conclusion

In order to solve the problem of serious energy consumption of melting aluminium furnace for smelting aluminium material, and recycle of energy of the heat flue gas to achieve the goal of saving fuel. To design the working process of the flue gas circulation and the heat energy recycling equipment of flue gas, use MATLAB software to deal with the heat balance calculation, system analysis and research on the data.

1) The cycle of circulation combustion for flue gas mixture is increasing the physical heat for heat income, which has the effect of preheating accelerant and recycle the heat energy, propellants is replaced of the traditional use of air mixture completely, and the combustion products will not have NOx compounds.
2) In the same conditions, respectively, using the heat balance calculation of ordinary combustion and circulation combustion of flue gas to calculate the heat balance, it has been verified by calculation that the effect of energy saving is obvious.
3) Advocating "more times" way of smelting and reducing aluminum material quality of the furnace each time, the aluminum has finished melting when the rate of heat absorption is not reduced too much, and then put in another new batch of aluminum material to keep every batch of aluminum smelting in effective stage.

References

[1] Liang CunKui, Li YiKe, Ren YanQiu.Application of the regenerative high temperature combustion technology in industrial furnace field[J].Journal of baotou iron and steel institute,2002,21 (3):14-16.
[2] IECKELE A O,NACCACHE M F,GOMES M S P,et al. Numerical Investigation of the Staged Versus Non-staged Combustion Process in an AluminumMelting Furnace[C]//Proceedings of AIAA/ASME Joint Thermophysics and Heat Transfer Conference.USA:ASME,1998:253-259.
[3] Dong JinLing,Ji JunHong. Development scheme of regenerative energy-saving burner development for small-scale aluminum melting furnace[J].Journal of liaoning engineering technology university (natural science edition),2010, 29:104-105.
[4] Zhou Hua,Wang Hao,Zhu ZhongMing.The heat balance calculation of regenerative heating furnace and the research of energy-saving technology[J].Metallurgical energy,2008,(6):22-26.27.
[5] Yan Kai,Zhang JianWen. Fuel combustion calculation analysis of oxy-fuel boilers[J].Boiler technology,2013,44 (1):35-40.
[6] Beichner F.L.Efficiency evaluation of melting aluminum furnaces[C].Light Metals,2002,725-729.
[7] Wang BingShuan. Industrial furnace design manual [M]. Bei Jing:Mechanical industry press,2010,143-169.
[8] Feng JunKai, Shen YouTing.Boiler principle and calculation [M]. BeiJing:Science press, 1998, 33-36.
[9] Tan YiJun, Zhou Ping.Numerical simulation and optimization on coupled multi-field of the regenerative cylindrical aluminum melting funace[D]. ChangSha:ZhongShan university,2011,25-26.
[10] Zhang XianZhao, Yi DanMo. The energy-saving technology and its calculation of industrial furnace[J].Industrial furnace,1998,21(2):21-27.
[11] Xu Hua.Research of high temperature air combustion technology [D].BeiJing: Beijing university of technology, 2002.
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