Estimation and Optimization Calculations of Alumina Flash Calciner

Vladimir Golubev[1], Dmitry Mayorov[2], Dmitry Finin[3], Edgaras Urbonavichus[4]
1. Head of Department
2. Lead Engineer
3. Chief Researcher
4. Lead Engineer
RUSAL ETC, St. Petersburg, Russia
Corresponding author: Vladimir.Golubev2@rusal.com

Abstract

Gas and dust flows parameters were measured and thermal imaging inspection of alumina flash calciner at RUSAL Kamensk Uralsky was carried out. A closed system of equations for steady-state mode of the flash calciner was developed. It is based on material and thermal balance equations including physicochemical transformations of material, PSD, and kiln hydrodynamics. Mathematical model was calibrated on the basis of the survey and automated control data. Kiln performance, specific fuel consumption, cyclone collection efficiency and other unit characteristics were further specified using this model. A study was conducted to determine the sensitivity of the kiln to changes in thermal regime of drying and calcination processes such as fluctuations in humidity and PSD of aluminum hydroxide, flow rates of air and dust on specific fuel consumption and kiln productivity. Based on the calculations it was established that intensive formation of alpha phase in produced alumina is associated with overheating of material in combustion prechamber of the calciner and in the flame of the burner in the dryer. Implementation of recommended solutions will improve kiln performance by 1 % and reduce the specific fuel consumption by 3 %.

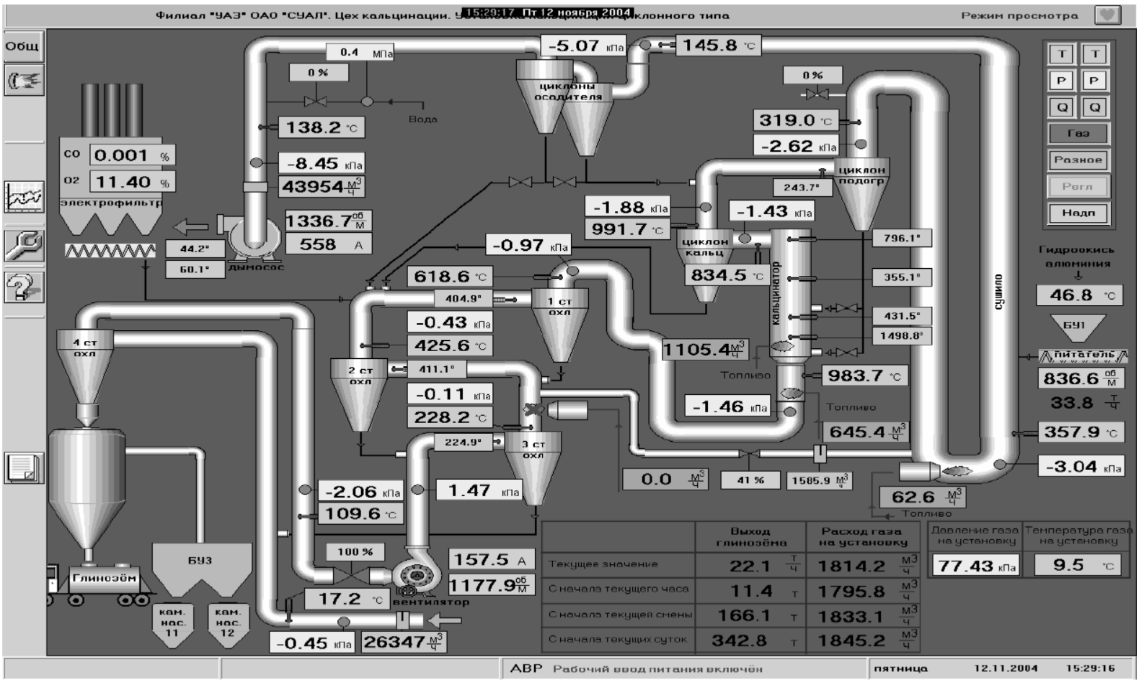
Keywords: alumina hydroxide flash calciner, digital twin, computational fluid dynamics.

1. Introduction

Stationary Calciners are widely used in alumina production since they allow obtaining alumina with low content of α phase at lower specific fuel consumption as compared to rotary kilns. Known in the art are modifications of Stationary Calciners: fluidized bed kilns, kilns with circulating bed, flash calciners. Recently many investigations are devoted to optimization of design and operational conditions of such stationary calciners for calcination of aluminum hydroxide [1-3].

A flash calciner at the Ural aluminum refinery was commissioned in 2004 and so far is the first and the only kiln unit of this type in Russia (Figure 1). It is constructed according to a conventional scheme, and comprises a pneumatic dryer, cyclone preheater, flash calciner, a four-stage cyclone cooler and a system for dust cleaning. Hydraulic resistance of the kiln is overcome by two fans, one of which pumps air in the cooler, and the other evacuates flue gases. The kiln is equipped with a system of sensors including thermocouples, flowmeters for natural gas and air and draught-and-head gauges [4].

From the moment of construction, individual changes were made in the design of the kiln, tuning of a combustion system of fuel that enabled to raise its productivity. A drawback of the system of sensors is the absence in its structure of reliable devices for measurement of hydrate and alumina consumption that led to misunderstanding of its actual productivity and specific data, and required a more accurate specification. Thus, the objective of this work was to assess the performance of the kiln at JSC RUSAL Kamensk-Uralsky and development of measures for its improvement.



	Выход глинозёма	Расход газа на установку
Текущее значение	22.1 т/ч	1814.2 м3/ч
С начала текущего часа	11.4 т	1795.8 м3/ч
С начала текущей смены	166.1 т	1833.1 м3/ч
С начала текущих суток	342.8 т	1845.2 м3/ч

Давление газа на установку	Температура газа на установку
77.43 кПа	9.5 °C

АВР Рабочий ввод питания включён
пятница 12.11.2004 15:29:16

Figure 1. Mnemonic scheme of kiln, 2004. [4].

2. A Closed System of Equations for Steady-State Mode of the Flash Calciner

Development of a detailed mathematical model based on the equations of the mass and thermal balance, population balance of particles and hydrodynamic calculations was considered as the most obvious way to solve the problem of assessing the current state of the flash calciner.

Balance equations of chemical substances and thermal energy are simple algebraic equations:

$$\sum \mathrm{m}_{\mathrm{A.out}} = \sum \mathrm{m}_{\mathrm{A.in}} + \sum \Delta\mathrm{m}_{\mathrm{A}}, \tag{1}$$

$$\sum \mathrm{Q}_{\mathrm{out}} = \sum \mathrm{Q}_{\mathrm{in}} + \sum \Delta\mathrm{Q}_{\mathrm{r}} - \mathrm{Q}_{\mathrm{loss}}, \tag{2}$$

where $\sum \mathrm{m}_{\mathrm{A.in}}$ and $\sum \mathrm{m}_{\mathrm{A.out}}$ – total mass flow rate of some substance *A* in flows at input and output from the device respectively, kg/s; Δm_A - a changing in amount of substance *A* as a result of chemical reactions within the considered device, kg/s; $\sum \mathrm{Q}_{\mathrm{in}}$ and $\sum \mathrm{Q}_{\mathrm{out}}$ - total heat fluxes presented by an enthalpy of the materials supplied and removed from the device, W; $\sum \Delta\mathrm{Q}_{\mathrm{r}}$ - total thermal effect of chemical transformations in the device, W; $\mathrm{Q}_{\mathrm{loss}}$ - amount of thermal losses to the environment, W.

For each flash calciner, mass balance equations are registered dividing the material flow into a number of output flows according to the set split factor x_i. In the aerosol state, heat exchange between this material and gas occurs promptly, consequently at the exit of any device of the kiln equality of temperature and material composition for all exit flows is established. Nevertheless, generally, heat exchange between gas flow and solid material can be incomplete, for example, due to uneven distribution of dust in the volume of the gas flow or partial slipping of material into downstream cyclone of a cooler unit. Assumption concerning equality of output temperatures and

chemical compositions facilitates significantly development of a topological diagram of the flash calciner.
The sequence of cyclone calculation by this model comprises three stages and is based on the following similarity equation [5]:

$$d_{50} = d_{50.st}\left(\frac{d}{d_{st}}\right)\left(\frac{u}{u_{st}}\right)^{-1}\left(\frac{\mu}{\mu_{st}}\right)\left(\frac{\rho_s}{\rho_{s.st}}\right)^{-1} \tag{3}$$

where d_{50} – cut size of cyclone, µm; u – average gas flow rate in the cross section of the cyclone, m/s; µ – viscosity of gas, Pa·s; ρ_s - gas density, kg/m^3; the lower index *st* designates characteristics corresponding to a standard cyclone.

PSD of aluminum hydroxide and produced alumina was checked for compliance to logarithmically normal distribution, which was confirmed. Taking this into account, an assumption was accepted that dust in all points of the kiln is logarithmically normal, which allowed to use this distribution law for calculation of integral factor of dust capture in all cyclones.

The following physical and chemical transformations of material were included into the kiln model:

- removal of free moisture:

$$H_2O_{(l)} \rightarrow H_2O_{(g)} \tag{4}$$

- decomposition of aluminum hydroxide:

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O_{(g)} \tag{5}$$

- Al_2O_3 recrystallization:

$$\gamma\text{-}Al_2O_3 \rightarrow \delta\text{-}Al_2O_3 \rightarrow \alpha\text{-}Al_2O_3 \tag{6}$$

The model assumes that in each device of the kiln (dryer, calciner, cyclones, electric precipitator, etc.) each of these processes can proceed, and probability and chemical extent of reaction depends on flow composition and chemical kinetics.

The rate of drying process (4) can be recorded through mass-transfer coefficient and driving force proportional to the difference of partial pressure of water vapor at a surface of a particle and in volume of a gas phase:

$$S_{dry} = \beta_{dry} f_{vol} \Delta P_w \tag{7}$$

where S_{dry} – reaction flow in the unit of volume of the drying device, kg/s/m^3; β_{dry} – configurable surface mass-transfer factor from the unit of particles surface area, kg/s/m^2; f_{vol} – particles surface in a volume of the device, m^2/m^3; ΔP_w – logarithmic mean potentials difference of drying process for conditions of co-current flow.

Chemical kinetics of reactions (5) and (6) is well described by the classical Arrhenius equation, and to take into account the difference in conditions of thermal treatment of material, it is multiplied with a correction factor individual for each device.

Capacity of the kiln is the result of a steady balance between possibility of fans and hydraulic resistance of the kiln. Dependences consumption-pressure and consumption-power for the fan and exhauster of the kiln of JSC RUSAL Kamensk-Uralsky were taken from the technical documentation. By known formulas calculation was made of the shift of these dependences at deviation of density, temperature and rotation speed of the fan from the specified values. An additional configurable factor considers wear degree of the wheel of exhauster which works in an abrasive gas-and-dust stream.

Pressure losses in the kiln are caused mainly by alteration in direction of gas-and-dust flow therefore its resistance law can be formulated as an additive sum of local resistance of cyclones, ducts, alternation of cross section:

$$\Delta P_{loss.total} = \sum \Delta P_{loss.i} = \sum \xi_i/2 \cdot \rho_{g.i} u_{g.i}^2 \tag{8}$$

where $\Delta P_{loss.total}$ and $\Delta P_{loss.i}$ – pressure losses in the kiln, respectively, total and at individual section; ξ_i, $\rho_{g.i}$ and $u_{g.i}$ – respectively, local resistance coefficient, density and stream velocity under actual conditions at the point of occurrence of local hydraulic resistance, -, kg/m^3 and m/s.

3. Assessment of Current State of the Kiln by the Results of Adjustment

Assessment of current state of the kiln was executed during adjustment of the mathematical model. Archived data from kiln operation were used for initial adjustment: temperature and pressure in devices, fuel and air consumption for burners of the dryer and calciner, moisture of aluminum hydroxide, LOI of alumina product, dust concentration in aerosol and solid substance composition at the exit from individual devices.

Reliable adjustment of the model requires at least two data sets for different historical periods with different thermal modes of the kiln. These data were collected in the course of inspection of the kiln. Before tool inspection, a scheme of sample selection was developed and sample access ports were executed by the course of the kiln path. Temperature measurements were carried out with the probe of gas analyzer "Polar-T", gas flow rate was measured with Pitot tube of Testo AG and a pneumometric tube of NIIOGAZ, dust from gas flow was selected with the use of "PZ BM Atmosphere" probes. In addition, the use was made of LOI and α-Al_2O_3 content in samples selected by refinery.

Adjustment of the model was performed in several stages: 1) adjustment of specific fuel and air consumption; 2) fitting of factors in kinetics equations of physical and chemical transformations in separate devices of the kiln; 3) adjustment at first of integrated, and then fractional coefficients of dust capture efficiency in cyclones; 4) creation of aerodynamic characteristics of hydraulic circuit.

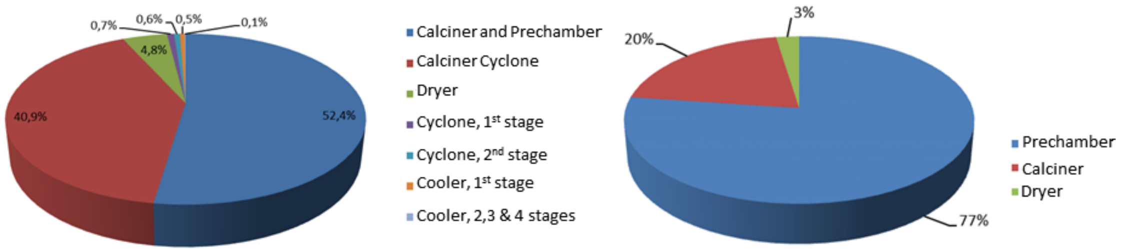
In Table 1 a comparison is given of temperature and dust consumption at the exit from individual devices of the kiln between actual measurements and results of model adjustment for one of operating modes of the kiln. One can observe that the temperature profile is reproduced in the model rather precisely, and the only significant divergence of unspecified nature is observed in gas temperature at the exit from the 1st cooler. Dust consumption carried over in the aerosol flow by the results of adjustment practically coincided with the results of measurements. Integrated factors of dust capture by cyclones were rather high that attests to the minimum amount of dead-weight circulating dust.

By the results of adjustment of kinetic equations, the contribution of each device of the kiln to the total degree of aluminum hydroxide calcination by reaction (5) was established.

Table 1. Results of temperature profile and dust consumption adjustment in the kiln.

Cyclone	Temperature at exit, °C		Dust consumption at exit, g/s		Cyclone capture efficiency, %
	Measurements	Calculations	Measurements	Calculations	
Cyclone, 2 st.	148,0	146,8	0,3	0,29	76,4
Cyclone, 1 st.	-		-		89,5
Preheater	319,2	329,5	1,9	1,92	92,1
Cyclone of calciner	877,8	868,9	13	12,35	82,7
Cooler, 1 st.	707,4	664,4	1,2	1,03	87,9
Cooler, 2 st.	472,3	505,7	8,1	8,55	91,2
Cooler, 3 st.	359,4	350,7	7,8	7,98	93,8
Cooler, 4 st.	189,9	193,6	7,7	7,7	94,1

In Figure 2 it is shown that the caciner accounts for a little over half of produced Al_2O_3 while about 40% of this product is formed in the cyclone of the heater and up to 5% in the tube drier. The remained 5% of alumina is formed as a result of reactions in cyclones-coolers.



a *b*

Figure 2. Distribution of the produced substances between individual units of the kiln: a - degree of $Al(OH)_3$ formation; b – degree of α-Al_2O_3 formation.

Actual measurements revealed increase in formation of α-phase in solid phase on the path between the cyclone-heater and settling cyclones by 1 – 2 %, i.e. from 1.5 to 3 % of corundum crystals are formed in the flame of the flash dryer. In the same way established that 20% of α-phase is formed in the calciner. The remaining part of α-Al_2O_3 amounting to two thirds of its total content in the product results from overheating of fine particles entering the prechamber from coolers.

Table 2. The results of chemical transformations of solid phase.

Point of sampling	Measurements			Calculations		
	Moisture	LOI	α-Al_2O_3	Moisture	LOI	α-Al_2O_3
Cyclone heater	< 0.01	23.9	< 1	-	20.4	0.76
Cyclone, 2 st.	0.08	29.1	1-2	-	30.2	0.12
Cyclone, 1 st.	0.02	33.5	-	-	31.3	0.12
Cooler, 4 st.	-	0.93	10-12	-	0.93	10.4
Electric precipitator				-	30.2	0.12
Calcination Unit				-	0.36	10.8
Cooler, 3 st.				-	0.93	10.4
Cooler, 4 st.				-	0.94	10.4
Cooler, 1 st.				-	1.02	10.4

4. Computational Investigation of Thermal Performance of the Kiln

There are not so many ways of increase energy efficiency of the kiln. It is possible to decrease specific fuel consumption by reduction of thermal losses through lining, lowering the temperature and reducing the amount of flue gases, LOI stabilization at the set level as well as by lowering the temperature of alumina at the exit. A series of calculations was carried out to assess the extent of impact of different factors on operation of the kiln, such as: hydrate humidity, PSD of hydrate, capture efficiency of cyclones, calcination temperature, air consumption for cooler, air consumption factor in the dryer and calciner, etc.

In the course of calculations it was established that in the operating kiln decrease in humidity of aluminum hydroxide fed to the kiln by 1 % leads to increase in output the by 0.25 t alumina /hour, to reduction in specific fuel consumption by 1.9 %, decrease in specific energy consumption by 1.5 %. Other opportunity to increase energy efficiency is increasing the maximum permissible LOI value of produced alumina at a level of 1% (Figure 3). Increase in LOI of produced alumina from current 0.79 to 1 % enables to decrease fuel consumption by 0.6 %. Various bypass circuits of material escaping calciner can be used for implementation of this opportunity. Such options as decrease in temperature in the calciner and changing capture factors of cyclones of the kiln of the operating design concerning specific fuel consumption are inefficient; previous improvements have already completely exhausted any possibility to decrease air consumption factor for the calciner and dryer.

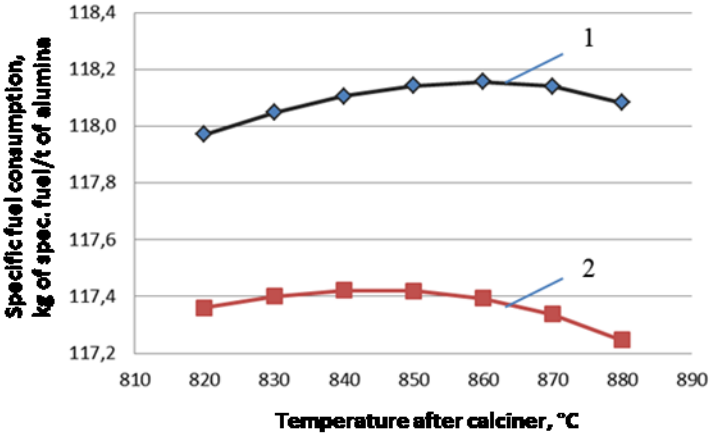
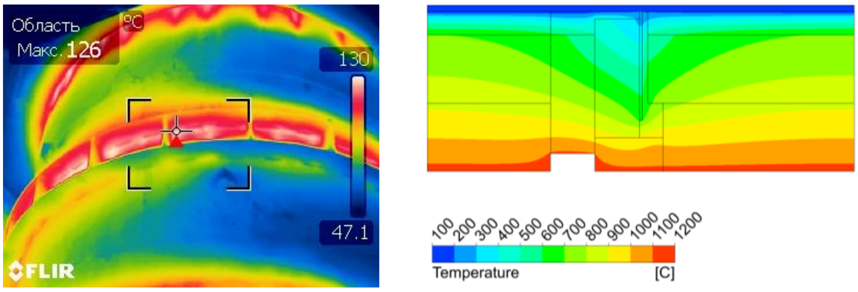


Figure 3. Influence of calcination temperature on specific fuel consumption for the modes: 1 – without hydrate bypass; 2 – hydrate bypass and LOI of alumina at a level of 1 %.

Of interest is also the conclusion made by the results of calculations that in operation with aluminum hydroxide of medium PSD (about 24 % - 45 µm fraction) the kiln can yield products with controllable and fixed LOI at a level of 1 %, and in case of coarsening or overgrinding of crystals it is impossible to obtain the target quality of product at any process conditions. In the first case, large particles do not have time to burn during their stay in the kiln. Secondly, due to the excessive presence of small particles, their entrainment from cyclones-precipitators to the electrostatic precipitator increases, and the bypass flow increases from the electrostatic precipitator to the cooler.

5. Change of Brickwork Pattern to Reduce Heat Losses of the Calciner

Balance thermal calculation showed that about 30 % of thermal losses accounts for thermal losses of the calciner through lining. In thermal scope pictures of the calciner on its external wall annular zones are clearly visible having temperature of 120 - 130 °C that correspond to position of support ring for refractory lining. As a result of thermal calculation of lining, it was established that at these areas metal reinforcing plates contact with a dense working bed of lining that promotes temperature increase of the body (Figure 4). The options of improvement in the brickwork pattern were recommended allowing to lower the temperature of the body to 90 - 100 °C, thus reducing thermal losses of the calciner by 1.3 times.



a *b*

Figure 4. Distribution of temperature on the surface of the calciner: a - thermal scope shooting, b - the result of calculation.

6. Investigation of Thermal Performance of the Calciner

Flash calciner is a complicated thermotechnical unit. Combustion of fuel in the unit is implemented in a diffusion mode, and burners of the prechamber are responsible for stabilization of a zone of burning in the calciner. Thus, the necessity to maintain steadily high temperature in the prechamber is caused by the design of the calciner. At the same time, as it is demonstrated by kinetic calculations, overburning of fine particles occurs in the prechamber resulting in formation of alpha phase.

In the course of integrated simulation of the kiln, a task was set to analyze possibility of stabilization of burning in the calciner at lowering thermal power of the prechamber and increase in gas consumption for burners of the calciner. Two options were studied: change of height of material feeding to the calciner and the impact of the angle of the burners of the calciner in a horizontal plane.

Both investigations were carried out with application of a package of computational fluid dynamics. The model comprised the following elements: burning was described by the model of previously unmixed burning, behavior of solids was described by the DPM model. Kinetics of chemical reaction in the solid phase was set by user defined function. Endothermic effect of the reaction of $Al(OH)_3$ dissociation was also considered. The problem was solved in a pseudo-stationary mode on the structured grid consisting of 3 million elements.

In the course of calculations it is established that stabilization of flame in the calciner occurs partially on the surface of burner tunnels, to a greater extent on the surface of lining of the kiln and significantly – in the flame of the prechamber. At decrease in thermal power of the prechamber in the point of material entry, an area is formed of lowered temperatures threatening flame failure. Division of the supplied material into two entry points located at different height of prechamber allows reducing this effect (figure 5).

It was supposed that the turn of burners in a horizontal plane, i.e. tangentially, will allow to create a more steady combustion center, however in calculations with a corner of burners turn at 10 and 20° from the central axis such effect was not observed (figure 6). It was noticed only at 30° when torches of burners came in touch, and combined in a steady general swirl. Nevertheless, this result was recognized as unsatisfactory since, firstly, particles of material became thrown to the walls of the calciner that reduced the quality of calcination, and then, manufacture of a burner block of such design involves considerable difficulties.

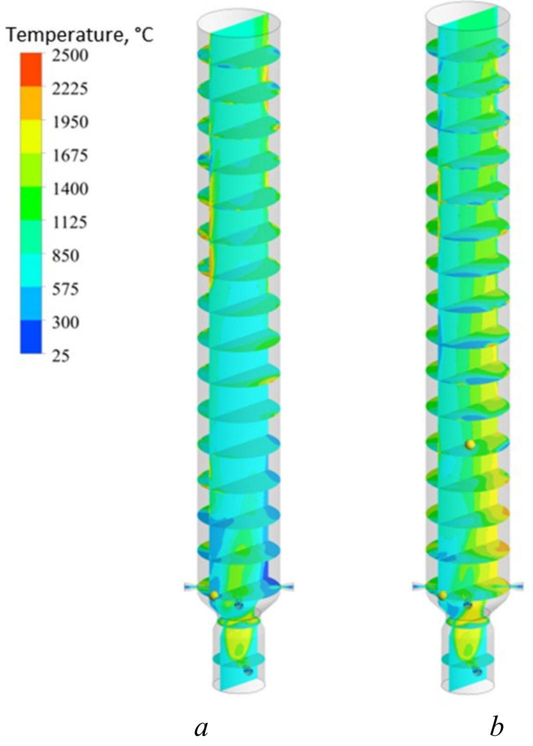


Figure 5. Temperature field inside the calciner at particles feeding (a) in one and (b) in two points at different height.

It is established that decrease in thermal power of the prechamber can be provided if material is supplied to the calciner not in one stream, but through two and more feed spouts at different height. This allows reducing the temperature at the exit from the prechamber by 10 °C, and α-Al_2O_3 content in alumina by 1.4 %.

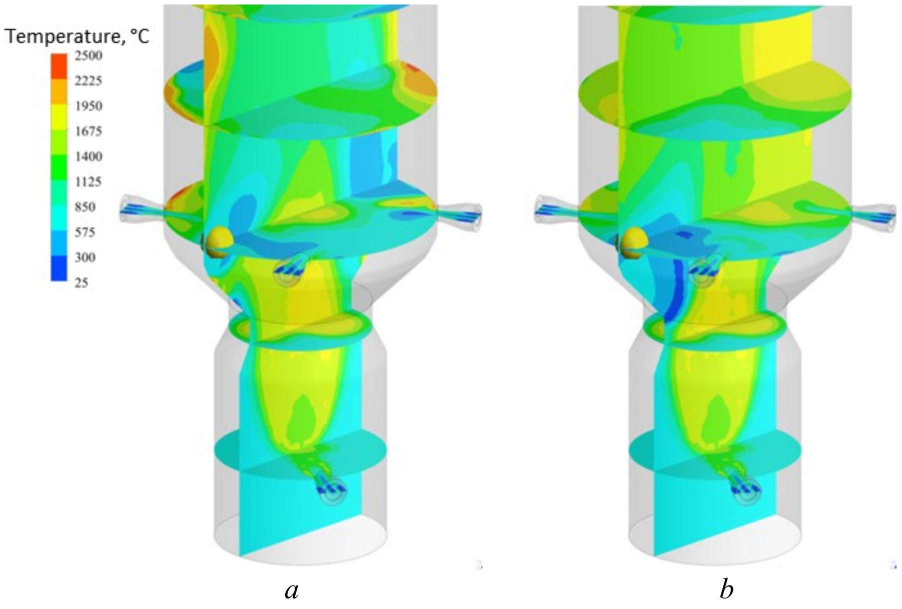


Figure 6. Thermal field in the prechamber and calciner at installation of burners with a turn of 20 ° and material fed in one (a) and two (b) points at different height.

7. Conclusion

An integrated mathematical model is developed of flash calciner of RUSAL Kamensk-Uralsky. Based on results of the measurements taken during instrumental inspection and on the basis of data of PCS, adjustment of the mathematical model is performed. The adequacy of the adjusted model to plant data is confirmed.

By numerical modeling on the basis of model of the kiln its current data are estimated, investigation of impact of process conditions and quality of calcined material on productivity, energy efficiency and chemical composition of produced alumina is conducted.

The share of each of kiln devices in achievement of final LOI of alumina is established by calculation, it is demonstrated that only 50 % in this distribution accounts for the calciner.

The most effective measures to increase energy efficiency and productivity of the kiln are determined: decrease in humidity of hydrate, stabilization of alumina LOI at the maximum allowed level due to bypass of material avoiding the calciner, reduction in thermal losses of the calciner. The reasons for high thermal losses of calciner are revealed and the way is proposed to decrease losses by 1.3 times due to change in brickwork pattern.

It is established that in the prechamber of the calciner and in the dryer the process of α-Al_2O_3 formation proceeds most actively, moreover up to 2/3 of this alumina modification is formed in the first device. It is proposed to lower the temperature in the prechamber by 10 °C and to feed the material into the calciner through two feed spouts at different height that allows reducing α-Al_2O_3 content in the products by 1.4 %.

8. References

1. Klett, C. Alumina Calcination: A mature technology under review from supplier perspective / C. Klett, L. Perander // Light Metals, 2015. P. 79-84.
2. Mr. Eberhard Guhl, Dr. Rolf Arpe "Nearly 30 years of experience with Lurgi calciners and influence concerning particle breakage" // Light Metals 2002, pp. 141-144.
3. Raahauge, B. Thermal Energy Consumption in Gas Suspension Calciners / B. Raahauge // Proceedings of 35th International ICSOBA Conference. Hamburg, Germany, 2 – 5 October, 2017. – P. 333-346.
4. Shishkin, S. F. Cyclone calcination kiln – an alternative to rotary kilns / S F. Shishkin, B.A. Fetisov//Innovations in material science and metallurgy: proceedings of the Ist International. Interactive. Sci.. - Pract. Conf. [13-19 Dec. 2011, Yekaterinburg]. – Yekaterinburg: Urals University Publishing House, 2012. – Part 1. – Page 132-136
5. Aliyev, G.M.-A. Equipment for dust capture and cleaning of industrial gases. Ref. book. / G.M.-A. Aliyev. M.: Metallurgy, 1986. 544 p.