EXPERIMENTAL AND CALCULATION-BASED FORECASTING OF FUEL CONSUMPTION ON ZINC-BEARING SLAG PROCESSING UNIT BASED ON PHASE INVERSION REACTOR

B. Dikhanbayev
K. Baubekov
A. Dikhanbayev
Kazakhstan, Astana, Agrotechnical University named after S. Seyfullin

Abstract

Using the afine (related) modeling, which foresee, based on test data of pilot plant, the necessity of correct calculation of conditional sample, is performed recalculation of pilot plant's test results on industrial sample. Having defined more precisely in mathematical description of process collection accountable factors, the list of basic numbers of similarity were obtained, on the basis of which is developed new technique of calculated estimation of fuel consumption in industrial sample of pilot plant. As a result of calculations it is shown that in comparison with fuming-furnace processing the liquid slag, on industrial sample of pilot plant the consumption of natural gas will be in two times lower, and with the increase of installation output in the range (5-25) t/h the specific consumption of natural gas will reduce in ~1, 5 times.

Keywords: Fuel consumption, phase inversion reactor

When developing high-temperature processes and equipment based on new technological ideas, the researcher often has to answer the following question:

- how should the "cold model" data, calculated on the basis of a number of assumptions, be transferred onto the pilot installation;

- how should the results of complex and labor-intensive pilot tests be transferred onto the future industrial equipment without excessive risk.

The method of similar physical analogs that requires mathematical description of the studied processes and its subsequent analyses by using similarity theory methods is used in practice for determining the basic parameters of the pilot installation, thereby answering the first question.

However, while satisfying the most stringent stipulations of the modeling process, this method leaves unanswered one or more similarity requirements, such as regarding losses into the environment, composition of the oxidant, etc. Therefore, a strictly similar implementation of the pilot installation based upon "cold" model testing is very approximate, albeit necessary.

To answer the second question, Prof. A.D. Klyutchnikov proposed the method of affine physical models. According to [1], this method, just as the method of similar models, requires recalculation of the model's evaluation data for parity of uniform similarity criteria to the sample that is similar to the given model. But this sample, denoted as provisory, together with the model, belongs to the affine series related to the forecasted sample and may have uncorrelatable calculated parameters. Therefore, the affine model method requires calculated correction of the provisory sample to align its individual parameters with the proposed operating conditions of the sample under consideration. For example, in a pilot installation with 2 t/hr capacity, at a = 0.8, the ratio of reducing gases (CO, H_2) to the reducible elements (Fe_3O_4, ZnO) is $(y+q)/(f+z)=3$.

To comply with similarity condition to the sample, i.e. $(y+q)/(f+z)=idem$, for a 12 ton sample, the air consumption coefficient must be α = 0.7.

Based on the similarity criteria, lets recalculate the actual data from the 2 ton model to the 12 ton provisory sample. After that, we shall calculate a fuel consumption correction for the provisory sample based on the dissimilarity of coefficient a between this provisory sample and the proposed 12 ton sample. We shall apply the corrected data to evaluate the parameters of the forecasted sample.

The waste slag processing unit is comprised of three main elements: inverted phase reactor, short rotary furnace, and high-temperature air heater. The reactor's effluent gases are used for preheating the waste slag and the blast air. The central element of the installation is the reactor that operates on a new technological principle - the phase inversion layer.

To build the "cold" reactor model, an evaluation methodology was developed for zinc reduction from slag in a phase inversion layer based on principles presented in [2]. Using this methodology and the test results of the gas-liquid reactor model we derived the following calculation path for reactor parameters of the pilot installation.

1. Data for calculations

Similarity criteria $W_C/W_{np}=12\text{-}25$; $I_C/G_B=0{,}09\text{-}0{,}19$, velocity of the gases in the nozzle array - W_c, temperature of the molten layer - t_p, temperature of the gases at the entry into the nozzle array and in the phase inversion layer - t_c, t_{np}, oxidant consumption coefficient - α, initial and final concentration of zinc in slag - C_H^{Zn}, C_K^{Zn}, number of nozzles - n_c and nozzle diameter d_c in the nozzle array. Here, W_{np} - normalized gas velocity within the phase inversion layer, $I_c=m_\Gamma \cdot W_c$ - kinetic momentum of the gas at the entry into the nozzles, m_Γ - mass flow rate of the gas at the entry into the nozzles, $G_B=M_B \cdot g$ - weight of the molten layer, M_B -mass of the bath layer, g - acceleration of gravity.

2. Natural gas consumption in the reactor

$B=\dfrac{3600\cdot W_C\cdot n_C\cdot 0{,}785\cdot d_C^2}{(1+\alpha\upsilon_B^0)\beta_C}$, here υ_B^0 - specific consumption of air for complete combustion of the natural gas, β_c - temperature coefficient of gas expansion before the nozzle array (in the combustion chamber).

3. Relative expansion of phase inversion layer is calculated by using the experimentally derived [3] formula that is valid within the variability range of $W_C/W_{np}=6\text{-}75$, $I_C/G_B=0{,}015\text{-}0{,}35$. $H/h_0=9{,}65(I_c/G_B)^{0,26}(W_C/W_{np})^{-0,19}$, where H-height of the expanded molten layer. The height of the "undisturbed" molten layer $h_0=M_B/\rho_P \cdot F_{np}$, where ρ_p- melt density.

The normalized phase inversion area $F_{np}=\dfrac{B(D+z)\beta_{np}}{3600\cdot W_{np}}$ [1], where β_{np} - temperature coefficient of gas expansion inside the phase inversion layer. $(D+z)$ -total specific volume of gases developed inside the layer.

4. Gas content of the layer $\varphi=1-h_0/H$

5. Time for complete mixing of the melt, $\tau_{\text{пер}}$, after introduction of a single concentration disturbance into the molten layer can be calculated by using the formula derived in [4] a valid within the ranges of

$W_C/W_{np}=12\text{-}25$, $I_C/G_B=0{,}09\text{-}0{,}19$:

$H_0 = \tau_{пер} \cdot g/W_C = 0{,}07(I_c/G_B)^{-0{,}6837}(W_C/W_{пр})^{0{,}0859}$,
here Ho - homochromy criterion.

6. Equivalent diameter of a molten particle within the layer, $d_Э$, can be calculated by using the equation derived in [5]:

$$\varphi = \left\{ \frac{\dfrac{W_{пр} d_Э}{\nu_Г C^n} + 0{,}02C^n \left[\dfrac{W_{пр} d_Э}{\nu_Г C^n} \right]^2}{1 + 0{,}02C^n} \right\}^{0{,}21},$$

here, the equation coefficients have the following values:

$C = (\frac{A}{B} d_Э^3$, $A = g\rho_P / \nu_Г^2 \rho_Г$ for $\mathrm{Re}_{вит} > 300$ n=0,5; B=1,21.

The approximate velocity of an individual particle movement can be calculated by using formula [6]:

$\mathrm{Re}_{вит} = Ar/(18 + 0{,}6\sqrt{Ar})$, $W_{вит} = \dfrac{\mathrm{Re}_{вит} \cdot \nu_Г}{d_Э}$ where $\rho_Г$, $\nu_Г$ are the density and kinematic viscosity of the gas.

7. Number of collisions between particles with concentration $C^{Zn} > C_K^{Zn}$ that are entering the layer and particles in the layer, having a concentration of $C^{Zn} < C_K^{Zn}$, until reaching the desired equilibrium concentration of C_K^{Zn} in the layer [2]:

$$n = 1{,}443X, \tag{2}$$

$$\theta = 1 - 3{,}385 \cdot A^{0{,}5} \cdot X^{-0{,}5} + 3AX^{-1}, \tag{3}$$

$$A = \frac{4D_{ZnO} \cdot \tau_{пер}}{1{,}443 \cdot d_Э^2}, \tag{4}$$

$$X = \ln \frac{C_H^{Zn} - C_K^{Zn}\theta}{C_K^{Zn}(1-\theta)}, \tag{5}$$

here, θ - average, dimensionless concentration of ZnO through the volume of the particle. D_{ZnO} - coefficient of zinc oxide molecular diffusion toward the surface of the particle.

Simultaneous solution of equations (3), (4), and (5) yields θ and then *n.*

8. Zinc sublimation time from the melt:

$$\tau_{воз} = \frac{\tau_{пер}(C_H^{Zn} - C_K^{Zn})}{n \cdot C_K^{Zn}(1-\theta)}.$$

9. Reactor productivity in terms of slag:

$$P_{ш} = \frac{3600 \cdot M_в}{\tau_{воз}}$$

10. Based on the calculated data, we can determine the geometric parameters of the pilot installation.

However, comparative data show that the results of experiments on the pilot installation (the sample) differ in productivity in terms of slag by more than 30% from the calculated values that were based on the gas/liquid model testing data. As indicated above, this is promoted by a number of unaccounted requirements of model similarity to the sample, such as high concentration of zinc ferrite $ZnFe_2O_4$ and magnetite Fe_3O4 that are fed into the reactor from the rotary furnace (RF) as a result of slag overoxidation caused by air leakage into the RF or by worsening of the reducing atmosphere in the reactor due to oxygen carried in with the slag charging process, etc.

After broadening and refining the totality of considered factors in the mathematical description of processes that occur in reactor of the pilot installation and having performed the appropriate conversions of the simultaneous equations and the boundary conditions, we obtain the list of main similarity criteria for the thermal operation of phase inversion reactor (PIR).

When the thermal operation of pilot installation PIR (the model) is similar to the production sample PIR, they will show the following similarity criteria.

1. Geometric similarity

$$H/h_0=idem,\quad D_{об}/d_{вых}=idem \qquad (6)$$

2. Aero- and hydrodynamic similarity.

$$W_C/W_{пр}=idem,\ W_C=idem$$
$$\tau_{пер}\cdot g/W_C=idem \qquad (7)$$

3. Similarity in specific productivity

$$\frac{p_\upsilon\cdot q_{пол}\cdot V^{СИФ}}{B\cdot(D+z)\cdot C_{ог}t_{ог}}=idem \qquad (8)$$

4. Thermal load similarity.

$$\frac{q_{OC}\cdot F_{OC}}{B\cdot(D+z)\cdot C_{ог}t_{ог}}=idem \qquad (9)$$

5. Technological process similarity

$$(y+q)/(z+f)=idem$$
$$\frac{\Delta C_Z}{C_Z}=idem,\ \frac{\Delta C_f}{C_f}=idem,\ \frac{q_{энд}}{C_{ог}t_{ог}}=idem,\ \frac{q_{пл}}{C_{ог}t_{ог}}=idem, \qquad (10)$$
$$\frac{t_ш}{t_{ог}}=idem,\ \frac{t_P}{t_{ог}}=idem,\ \frac{t_{пл}}{t_{ог}}=idem$$

Here, $D_ц$, $d_{вых}$ – diameters of the cyclonic section and the gas outlet port of the reactor, p_υ - specific productivity of PIR, $q_{пол}$ - productively used heat energy in reactor, $V^{СИФ}$ - volume occupied by phase inversion layer, $C_{ог}$, $t_{ог}$ -specific heat and temperature of exhaust gases, q_{OC} - average heat density across the PIR lining, F_{OC} - PIR hot surface, y, q, f, z - number of moles of CO, H_2, Fe_3O_4, and ZnO taking part in reduction, per mole of natural gas, ΔC_f, ΔC_Z – part of Fe_3O_4 and ZnO reduced during the process, C_f, C_z - initial concentration of Fe_3O_4 and ZnO in granulated slag, $q_{энд}$ - average specific endothermic effect of Fe_3O_4 and ZnO reduction, $q_{пл}$ - specific heat of slag melting, $c_ш$ - specific heat of molten slag, $t_ш$, t_P - slag feed and molten slag temperatures, $t_{пл}$ -slag melting temperature.

Based on the evaluated similarity conditions between the model and the sample, we can calculate the sample parameters in the following sequence.

1. Having set an arbitrary value "B" for natural gas consumption in the process, we can determine the composition of exhaust gases by using formula [7]:

$$(K-1)x^2+[K(B_C+C_{H_2}-2E_{O_2}-z-4f)+2E_{O_2}+z+4f]x-B_C(2E_{O_2}-$$
$$-B_C+z+4f)=0,$$
$$z=\frac{P_ш\Delta C_Z\cdot 22{,}4}{81\cdot B},\quad f=\frac{P_ш\Delta C_f\cdot 22{,}4}{232\cdot B},\quad y=B_C-x$$
$$w=2E_{O_2}-B_C-x-z-4f,\ q=C_{H_2}-w,\ D=A_{N_2}+B_C+C_{H_2},$$
$$Zn^{Г}=\frac{z}{D+z},\ CO=\frac{y}{D+z},\quad H_2=\frac{q}{D+z} \qquad (11)$$

Here, K - equilibrium constant of $CO_2 + H_2 \leftrightarrow CO + H_2O$, reaction, *x*, *w*-number of moles of CO_2 and H_2O, respectively, per 1 mole of natural gas. A_{N_2}, B_C, C_{H_2} respective number of moles of nitrogen, carbon, and hydrogen that took part in the process, per 1 mole of natural gas, CO, H_2, Zn^{Γ} - absolute shares of these components in the exhaust gas.

2. The unknown natural gas consumption for the "sample" can be determined by using the formula derived from the reactor's thermal balance equation

$$B = \frac{P_ш[t_p - t_ш) + q_{пл} + q_{энд} - (\Delta C_Z + \Delta C_f)c_ш t_ш] + F_{OC} \cdot q_{OC}}{Q_н^P + \alpha \upsilon_в^0 c_в t_в - (D+z)[c_{ог} t_{ог} + CO \cdot q_{CO} + H_2 q_{H_2} + Z_n^{\Gamma} \cdot q_{Zn}]}$$

Lets identify:

$$c_ш(t_P - t_ш) + q_{пл} + q_{энд} - (\Delta C_Z + \Delta C_f)c_Ш t_Ш] = a,$$

$$Q_H^P + \alpha \upsilon_в^0 \cdot c_в t_в - (D+z)[c_{ог} t_{ог} + CO \cdot q_{C_0} + H_2 q_{H_2} + Zn^{\Gamma} \cdot q_{Zn}] = в,$$

then $$B = \frac{P_Ш \cdot a + F_{OC} \cdot q_{OC}}{в}, \qquad (12)$$

The empirical expression for the reactor's hot surface, [7]:

$$F_{OC} = 12{,}5 \cdot H\sqrt{F_{пр}} + 15 \cdot F_{пр}, \qquad (13)$$

Transforming equation [1]:

$$\frac{(D+z)\beta_{пр}}{3600} = c, \; F_{пр} = \frac{B \cdot c}{W_{пр}}, \qquad (14)$$

Solving equations (12), (13), and (14) simultaneously, we derive the equation for fuel consumption:

$$(в - 15 \cdot c \cdot q_{OC} \cdot W_{пр}^{-1})B - (12{,}5 \cdot c^{0,5} \cdot q_{OC} W_{пр}^{-0,5})H \cdot B^{0,5} - aP_Ш = O \qquad (15)$$

By varying values of Hj in (15), we find a series of values for B_i. By substituting B in (14), we determine $F_{прi}$. Properly derived value of fuel consumption must satisfy the condition –

$$(H_i \cdot F_{прi}) = V^{СИФ}, \; (V^{СИФ})^{обр} = \frac{(P_Ш)^{обр}}{(P_V)^{модель}}, \qquad (16)$$

We now compare the derived value of B_i with the previously set value of "B". If $B_i \neq B$, we repeat the calculation to derive this equality.

Table 1 shows the application of pilot installation test data results to the production sample by using affine modeling method. A "rich" waste slag from lead-smelting operation was used in the experiments.

The table data refer to a reactor with lined cyclonic section and direct natural gas combustion (without a combustion chamber).

Main similarity criteria found during testing:

1. $H/h_0 = 3{,}27$; $D_{об}/d_{вых} = 1{,}6$.
2. $W_C/W_{пр} = 17{,}55$; $W_C = 550 m/s$; $I_C/G_в = 0{,}1277$.
3. $\frac{P_V' \cdot q_{пол} \cdot V^{СИФ}}{B(D+z)c_{ог} t_{ог}} = 0{,}4243, \; \frac{P_V'' \cdot q_{пол} \cdot V^{СИФ}}{B(D+z)C_{ог} t_{ог}} = 0{,}666,$

where $P_V' = 6050$ kg/m^3·hr for E =85%; $P_V'' = 9500$ kg/m^3·hr E = 65% for extracting zinc from the melt.

4. $\frac{q_{OC} \cdot F_{OC}}{B(D+z)c_{ог} t_{ог}} = 0{,}76, \; q_{OC} = 140 \; kW/m^2$
5. $\tau_{пер} \cdot g / W_C = 0{,}3656.$

6. $t_{Ш} = 900^0 C,\ t_p = 1350^0 C, t_{ОГ} = 1450^0 C.$

Table 1 **The calculation results**

1	Reactor productivity in terms of slag		5,0	12.0	25.0
2	Natural gas consumption, nm^3 /hr	E=65%	560	1062	1800
		E=85%	851	1600	2680
3	Reactor specific fuel consumption, nm^3 /tZn	E=65%	112	89	72
		E=85%	170	133	107
4	Reactor hot face, m^2		23	40.5	67.7

According to [9], when processing liquefied slag with E=65-75% at the Chimkent slag-sublimation plant, the specific consumption of natural gas was 200 -230 nm^3/tZn.

The following conclusions can be drawn from the data in Table 1 for the proposed unit for processing zinc-bearing slag:

1. Compared to the fuming furnace at Chimkent lead plant that processed liquefied slag, the specific consumption of natural gas will be cut in half.
2. As the productivity of the unit will increase in the 5-25 ton/hr range, the specific consumption of natural gas will decrease by a factor of 1.5

References:

A.D. Klyutchnikov Thermotechnical optimization of fuel-burning. M.: Energy. 1974. 343 p.

B.I. Dikhanbayev Methodology for calculated productivity evaluation of reactors for processing lead-bearing slag. Collection of scientific reports. Moscow Energy Institute. 1988. № 176, p.47-51.

V.A. Ippolitov Improving the efficiency of melting granulated materials in a fluidized bed process. Dissertation of Candidate of Tech. Sciences. M.: 1982.

B.I. Dikhanbayev, A.B. Dikhanbayev Experimental studies of mixing times in KCP type reactor. Publications of Southern Kazakh State University, 1999. p. 140-142.

A.D. Klyutchnikov, V.A. Ippolitov On the method of calculating heat exchange under conditions of highly forced blow-through across the molten Publ. of Moscow Energy Institute. 1979, issue 394, p. 63-67.

M.E. Aerov, O.M. Todes Basic hydraulic and thermal parameters of apparatus with stationary and fluidized bed of granular materials. Л.: Химия. 1968.

B.I. Dikhanbayev Development of intensive energy-conservation measures in lead-smelting slag fuming systems. Dissertation of Candidate of Tech. Sciences M.: 1991.

B.I. Dikhanbayev, A.B. Dikhanbayev Calculation of fluidized bed melting parameters for lead-bearing slag fuming operations. Publications of Southern Kazakh State University. 1999. Vol. 2, p. 134-136.