Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Multi-variable Control for HPAL Using Nonlinear Multivariable Decoupling PID Control based on Predictive Model

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Abstract: High pressure acid leaching process is the use of strong acid slurry in the high temperature & pressure conditions, and acid leaching to useful metal ions process. It is a typical multiple-input multiple-output system. The efficiency of acid leaching is sensitively influenced by temperature, pressure and level of the autoclave, and in general the single loop PI method is always adopted for designing each loop controller. But due to the coupling effects among those variables, the method cannot control the temperature, pressure and level stable, which result in the decrease of efficiency of acid leaching. By analyzing high pressure acid leaching characteristics a nonlinear decoupling predictive control approach is employed based on mechanistic models established. The method has been successful applied to a real large-scale abroad nickel hydroxide cobalt smelt plant. The results demonstrate that the method can effectively and steadily control the temperature, pressure and level of the autoclave at their targets nearby, and improve the efficiency of acid leaching.

Key words: high pressure acid leaching process, MPC, multi variable, nonlinear, decoupling control, leaching rate.

1. INTRODUCTION

High pressure acid leaching (HPAL) is a process to combine the incoming pulp and strong acid solution under a high temperature and pressure environment to produce the qualified pulp for the subsequent procedure. In the process, the autoclave is widely used to provide a high temperature, high pressure and strong acid environment for leaching cobalt and nickel. The leaching rates of cobalt and nickel are determined by the autoclave temperature, pressure, level, and the flow of adding acid[1][2],Therefore, to obtain a satisfactory leaching efficiency, in the HPAL process the autoclave temperature, pressure and level must be controlled at the target values, while guaranteeing the temperature, pressure and level against fluctuations.

The autoclave as a typical continuous stirred tank reactor is characteristic of high temperature and high pressure. In[3][4][5] for a compartment autoclave temperature, the valve opening as input, the autoclave temperature as output, respectively a temperature model based predictive control method and employs unscented Kalman filter based nonlinear model predictive control method to the autoclave inner temperature set-point control, and theoretical analysis and semi-physical simulation show the validity the effectiveness of this method. in [6] used a method which combine PID and adaptive pole assignment is used to control the temperature of the autoclave with two compartments. In [7][8] used a a method called L-QDMC and a NMPC method to control the temperature of the autoclave with multi-compartments, and the simulations prove that this method is better than the traditional PI controller in the dynamic characteristic of close loop system. This control method only considerate that the autoclave inner temperature. However, in this paper in order to get a higher nickel and cobalt leaching rate, not only need to considerate the autoclave inner temperature, but also the autoclave pressure and the level were need to set-point control. In [9], an integrated process model for HPAL is established firstly, to predict the process variables including the inner temperature, pressure, pulp flow, concentration of steady state and dynamic process. Unfortunately, due to the established model complexity and too many hypotheses, this model can not be applied to the real plant.

Responding to HPAL with characteristic of the multivariate, nonlinear, strongly coupling, a nonlinear decoupling predictive control approach is employed to realize the stable control of temperature, pressure and level of autoclave. The application in a large nickel and cobalt smelter foreign high pressure acid leaching process, the autoclave temperature, pressure and level within the target range while controlling the process required to obtain a satisfactory control effect.

2. HPAL PROCESS CONTROL PROBLEM DESCRIPTION

2.1 HPAL process description

The incoming material of HPAL as shown in Fig.1 is the pulp from last process and the final product is the pulp leached through the autoclave.

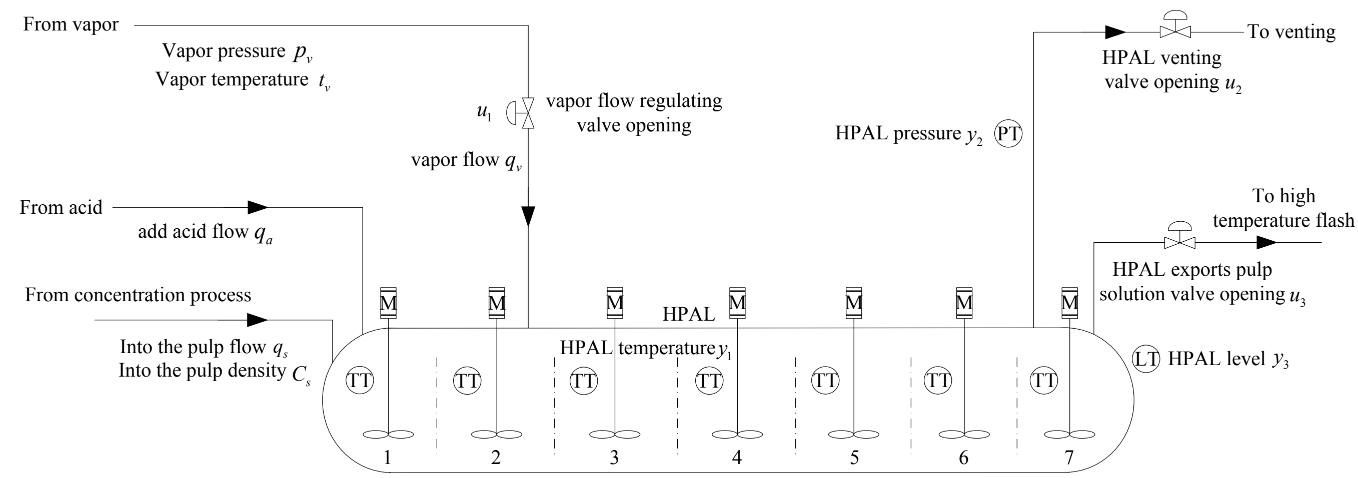

Fig. 1. The flow sheet and present control status of HPAL process

The pulp from the concentration process is sent to the autoclave by the feed pump. Meanwhile, the sulfuric acid q_a, and high pressure steam q_v are added to the autoclave. The heat of high pressure steam, the dilution and reaction heat of sulfuric are used to make the temperature of pulp meet the requirement of the process. At the same time, keeping the pressure and liquid level of the autoclave, the nickel and cobalt can react with sulfuric acid under the regulation of high temperature and pressure. The product containing nickel and cobalt is sent to the subsequent process. The advantage of this process is the low energy consumption and the high rate of the recovery of nickel and cobalt [10].

The indicator of the high pressure acid leaching is the rate of nickel and cobalt leaching. The control objective is to achieve the requirements of nickel and cobalt leaching rate and keep the temperature, pressure and liquid level in the target value nearby. That is:

$$\begin{cases}\gamma_1(t) \geq \gamma^*_{Ni} \\ \gamma_2(t) \geq \gamma^*_{Co}\end{cases} \Rightarrow \begin{cases} y_1(t) = y_1^* \\ y_2(t) = y_2^* \\ y_3(t) = y_3^* \end{cases} \tag{1}$$

γ^*_{Ni} and γ^*_{Co} are the process indicators of nickel and cobalt leaching rate. y^*_1 y^*_2 and y^*_3 are the target value of the temperature, pressure and level of autoclave. The t is the sampling time.

The task is to design a controller for the autoclave. And the steam valve position $u_1(t)$, the opening of exhaust valve $u_2(t)$, and the opening of discharge valve $u_3(t)$ are the inputs of the controller. And the temperature of autoclave $y_1(t)$, the pressure of autoclave $y_2(t)$, the level of the autoclave $y_3(t)$ are the outputs of the controller. It is used to realize the control target.

2.2 Dynamic model

The main economic indicator of high pressure acid leaching process is the nickel and cobalt leaching rate. It is decided by the flow and concentration of feed pulp and the acid, the temperature and pressure of autoclave and the residence time of pulp in autoclave.

According to the literature [11][12], the dynamic model of temperature in autoclave is established:

$$\begin{cases} \dot{y}_1(t) = \dfrac{\varphi(t_v(t), p_v(t))u_1(t)\sqrt{\dfrac{p_v(t)-y_2(t)}{f_1[t_v(t)+273.15]}}}{C_{sc}C_s(t)q_s(t)} + \dfrac{\pi\dfrac{4R^2-1}{2}[y_3(t)]^2 LC_{ps}Q_t(t)K_{s0}e^{-\frac{E}{R_p\cdot y_1(t)}} - u_2(t)\varphi(t_v(t), p_v(t))\sqrt{\dfrac{y_2(t)\text{-}p_0}{f_t[y_1(t)+273.15]}}}{C_{sc}\cdot C_s(t)\cdot q_s(t)} \\ \qquad - \dfrac{A\lambda_1\lambda_2(y_1(t)-y_1(0))}{(\sigma_1\lambda_2+\sigma_2\lambda_1)C_{sc}C_s(t)q_s(t)} \\ \dot{y}_2(t) = \dfrac{10752-10y_1(t)-4.3\cdot 10^{5.1463-\frac{1540}{273.15+y_1(t)}}}{R_p(273.15+y_1(t))^2}y_2(t)\dot{y}_1(t) + \dfrac{Q_t(t)}{I_t(t)} - k_2(y_2)u_2(t) \\ \dot{y}_3(t) = \dfrac{u_1(t)\sqrt{\dfrac{p_v(t)-y_2(t)}{f_1[t_v(t)+273.15]}} - u_2(t)\sqrt{\dfrac{y_2(t)\text{-}p_0}{f_t\cdot[y_1(t)+273.15]}}}{2\sqrt{y_3(t)[2R-y_3(t)]}L\rho_t(y_1(t),\ y_2(t))} + \dfrac{q_s(t)+q_a(t)-k_3\sqrt{\dfrac{y_2(t)-p_3}{\rho_3(t)}}}{2\sqrt{y_3(t)[2R-y_3(t)]}L} \end{cases} \tag{2}$$

C_{sc} is the heat capacity of feed pulp, V_s is the volume of pulp in autoclave, C_{ps} is the specific heat, Q_t is the dilution and reaction heat between sulfuric acid and pulp, R is the radius of both circular sides of autoclave, L is the length of autoclave, K_s is the reaction rate between pulp and sulfuric acid, K_{s0} is the frequency factor, E is the reaction activation energy, R_p is ideal gas constant, A is the autoclave surface area, σ_1, σ_2 are steel and titanium thickness of autoclave, λ_1 and λ_2 are steel and titanium thermal conductivity coefficient, $\varphi(\cdot)$ is the enthalpy for steam under different temperature, different pressure, q_{u2} is the exhaust flow, p_0 is the standard outdoor atmospheric pressure, f_t is the gas drag coefficient of exhaust. A_l is cross sectional area of autoclave, ρ_t is the steam density.

It can be seen from formula (2), the model analysis and the physical properties of the autoclave, it can be seen the process is a typical multi variable, nonlinear, strong coupling, time-varying industrial process, at the same time, for the multi-control process conditions which include the static elevated temperature, dynamic elevated temperature and pressure, in the initial addition of acid process, in the mine acid leaching process, etc.

3. MODEL PREDICTIVE BASED MULTIVARIABLE NONLINEAR DECOUPLING CONTROL METHOD

3.1 Control strategy

As shown in Fig.2, Model predictive based multivariable nonlinear decoupling control was made of model prediction, nolinear compensation, decouple compensation and PID controller.

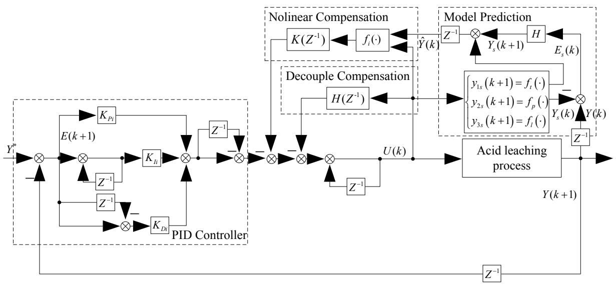

Fig. 2. The structure of model predictive based multivariable nonlinear decoupling PID controller

3.2 Control algorithm

Model prediction based multivariable nonlinear decoupling PID control algorithm consists of model prediction, nonlinear compensation, decoupling compensation and PID control. Due to the existence of a large time delay in HPAL process, this paper uses the prediction model module to eliminate the influence brought by the large time delay. The model module mainly includes temperature, pressure and liquid level in the autoclave and the correction parameters, which estimates the output value according to the control value, model parameters and calibration parameters. The nonlinear compensation module uses $K(Z\text{-}1)$ is Z-1 diagonal polynomial matrix, in order to eliminate the effects of nonlinear term $F(\cdot)$ on the closed-loop system. The decoupling compensation module uses the $H(Z\text{-}1)$ is Z-1 polynomial matrix and the diagonal elements are zero, in order to eliminate the influence of coupling term in the linear model. PID control module is used to make the output $Y(k)$ track the set value Y^*. The control structure is shown as Fig.2.

3.2.1 Model prediction algorithm

In this paper the mechanism of acid leaching process model as a predictive model, at the same time, In order to eliminate the error between predictive model and the actual system, the open-loop prediction should be corrected, and the output of the predictive model should be installed feedback correction link in order to form a closed-loop prediction[13].

This paper corrects the control of predictive model through the error between the output of predictive and actual system. The actual output of the system at the k sampling time is $Y(k)=[y_1(k), y_2(k), y_3(k)]^T$, the output of the prediction model is $Y_s(k)=[y_{1s}(k), y_{2s}(k), y_{3s}(k)]^T$, the estimation error is $E_s(k)=Y(k)\text{-}Y_s(k)$, the output of the predictive model can be corrected by the weighting of $E_s(k)=[e_{1s}(k), e_{2s}(k), e_{3s}(k)]^T$ and the prediction $Y_s(k+1)$ of the prediction model at next moment.

$$\begin{cases} \hat{y}_1(k+1)=y_{1s}(k+1)+h_1\cdot e_{1s}(k) \\ \hat{y}_2(k+1)=y_{2s}(k+1)+h_2\cdot e_{2s}(k) \\ \hat{y}_3(k+1)=y_{3s}(k+1)+h_3\cdot e_{3s}(k) \end{cases} \tag{3}$$

$H=(h_1, h_2, h_3)^T$ is error correction coefficient

3.2.2 Nonlinear decoupling PID control algorithm

Nonlinear PID control mainly includes the nonlinear compensation controller, the decoupling compensation controller and PID controller. The formula (2) can be simplified to the following approximate linear model and nonlinear model:

$$\begin{pmatrix} y_1(k+1) \\ y_2(k+1) \\ y_3(k+1) \end{pmatrix} = \begin{pmatrix} 1-TK_{u11}+Z^{-1}TK_{u11} & 0 & 0 \\ 0 & 2-TK_{u11}-Z^{-1}(1-TK_{u11}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} y_1(k) \\ y_2(k) \\ y_3(k) \end{pmatrix} + \begin{pmatrix} TK_{1u1} & -TK_{1u2} & 0 \\ K_{y2}TK_{u1}(1-Z^{-1})Z^{-1} & K_{y2}TK_{u2}(1-Z^{-1})Z^{-1} & 0 \\ TK_{3u1} & -TK_{3u2} & -TK_{3u3} \end{pmatrix} \begin{pmatrix} u_1(k) \\ u_2(k) \\ u_3(k) \end{pmatrix} + \begin{pmatrix} f_1(k) \\ f_2(k) \\ f_3(k) \end{pmatrix} \tag{4}$$

T is the sampling period

$$\begin{cases} f_1(k)=TK_{y1}[y_3(k)]^2 e^{-\frac{E}{R_p\cdot y_1(k)}} \\ f_2(k)=K_{y2}TK_{y1}\left\{[y_3(k-1)]^2 e^{-\frac{E}{R_p\cdot y_1(k-1)}} - [y_3(k-2)]^2 e^{-\frac{E}{R_p\cdot y_1(k-2)}}\right\} \\ \qquad +T\frac{Q_t(k)}{I_t(k)} - T\frac{(1-TK_{u11})Q_t(k-1)}{I_t(k-1)} + K_{y2}TK_{u11}\left[y_1(k-2)-y_1(k-3)\right] \\ f_3(k)=TK_{3q}\left[q_s(k)+q_a(k)\right] \end{cases}$$

$$\begin{cases}
K_{1u1}(k)=\dfrac{\varphi\left(t_v(k),\ p_v(k)\right)}{C_{sc}C_s(k)q_s(k)}\approx K_{1u1} \\
K_{1u2}(k)=K_{1u1}(k)\sqrt{\dfrac{y_2(k)\text{-}p_0}{f_t\left[y_1(k)+273.15\right]}}\approx K_{1u2} \\
K_{y1}(k)=\dfrac{\pi\left(4R^2-1\right)LK_{s0}C_{ps}Q_t(k)}{2C_{sc}C_s(k)q_s(k)}\approx K_{y1} \\
K_{u11}(k)=\dfrac{A\lambda_1\lambda_2}{C_{sc}C_s(k)q_s(k)\left(\sigma_1\lambda_2+\sigma_2\lambda_1\right)}\approx K_{u11} \\
K_{y2}(k)=T\dfrac{y_2(k)\left(10752-9.9y_1(k)-4.3\cdot 10^{5.1463-\frac{1540}{y_1(k)+273.15}}\right)}{R_p\left(273.15+y_1(k)\right)^2}\approx K_{y2} \\
K_{3u1}(k)=\dfrac{1}{2\sqrt{y_3(k)[2R-y_3(k)]}L\rho_t\left(y_1(k),\ y_2(k)\right)}\approx K_{3u1} \\
K_{3u2}(k)=\dfrac{\sqrt{\dfrac{y_2(k)\text{-}p_0}{f_t\left[y_1(k)+273.15\right]}}}{2\sqrt{y_3(k)[2R-y_3(k)]}L\rho_t\left(y_1(k),\ y_2(k)\right)}\approx K_{3u2} \\
K_{3u3}(k)=\dfrac{K_q}{2\sqrt{y_3(k)[2R-y_3(k)]}L}\approx K_{3u3} \\
K_{3q}(k)=\dfrac{1}{2\sqrt{y_3(k)[2R-y_3(k)]}L}\approx K_{3q}
\end{cases}$$

It can be seen from the formula (4), the nonlinear part makes a bigger influence on system. Therefore, the controller should be designed aiming at the big change of the nonlinear part. According to Fig.3, the control variable can be expressed (5), According to the literature [14] can be solved K_P, K_I, K_D, H, K.

$$\begin{aligned}U(k)&=U(k-1)+K_P\left[E(k)-E(k-1)\right]+K_IE(k)\\&+K_D\left[E(k)-2E(k-1)+E(k-2)\right]-H\left(Z^{-1}\right)U(k)-K\left(Z^{-1}\right)F(k)\end{aligned} \tag{5}$$

3.2.3 Steam flow PI control algorithm

The set value of the flow of steam can be obtained according to the control. PI control algorithm should be used to track the set value in order to reduce the fluctuation of steam.

4. SYSTEM IMPLEMENT AND INDUSTRIAL APPLICATIONS

The method of multi-condition switching control by this paper is used for industrial experiment, in order to verify its validity and practicability.

4.1 Application object description

The high pressure acid leaching process in a large nickel cobalt smelting plant is shown as Fig.3. The HPAL process is composed of autoclave and ancillary equipment described by this paper. Autoclave is a horizontal vessel (model: 34m in length, 5.1m in diameter, weighing about 800 tons). The boiler of the autoclave is welded by steel. Titanium is covered the inner of the autoclave. The thickness of shell is 118mm, and the titanium is 8mm.

The control target is y^*_1=255℃, y^*_2=4500KPa, y^*_3=50%. The leaching rate required by the process is γ^*_{Ni}=95.5%, γ^*_{Co}=95%.

Fig. 3. The high pressure acid leach process

4.2 Control system hardware platform

The hardware platform of the nickel cobalt neutralization process control system is shown as Fig.4.

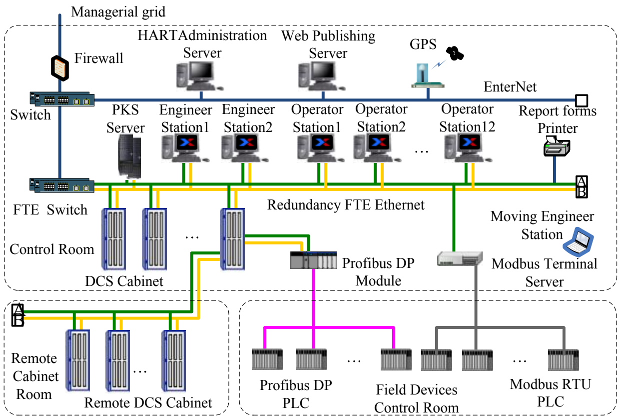

Fig. 4. Control system hardware platform for acid leaching nickel and cobalt hydroxide process

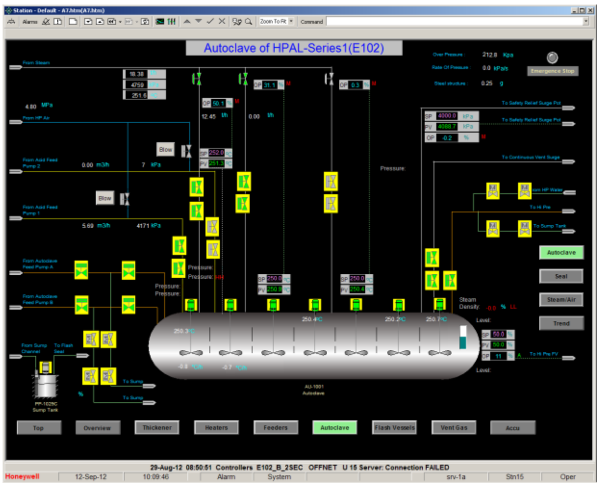

Fig. 5. Monitoring view of HPAL process

According to the operation process and equipments of high pressure acid leaching, HMI is designed as shown in Fig.5.

The hardware consists of the mature process knowledge system Experion-PKS-300, 1 HART management server, 1 web server, one GPS clock, 2 DELL T5400 engineer stations, 12 sets of DELL operator stations, some DCS system cabinets, a number of remote DCS system cabinets, and the corresponding instrumentation, electrical equipment, actuators.

4.3 Control parameter selection

The valve opening is adjusted to K_{pt}=1, T_{it}=0.2; The sampling period T=1s. The parameters of the temperature preset model are A=585.31m^2, σ_1=0.11m, σ_2=0.008m, λ_1=52w/m ℃ , λ_2=29.31w/m ℃ , V_l=0.8V=384m^3, m_l=240000kg, $\varphi(tz)$=2493.18kj/kg, The multivariable nonlinear decoupling based model prediction controller is K_P=diag(0.7, 0.5, 0.6), K_I=diag(1.8, 2.0, 1.0), K_D=diag(0.0, 0.0, 0.0), H=(Z^{1}) is *a* 3×3 matrix and the side diagonal elements is 0.64-0.64Z^{1}, 0.33-0.33Z^{1}, 0.21-0.21Z^{1}, the other elements is 0, $K(Z^{1})$=diag(0.53-0.53Z^{1}, 0.73-0.73Z^{1}, 0.31-0.31Z^{1}).

4.4 Application effect analysis

In the high pressure acid leaching process control system was innovation before. This process has been using conventional PI methods. The history curves of the autoclave inner temperature $y_1(t)$, pressure $y_2(t)$ and level $y_3(t)$ shown in Figure 6.

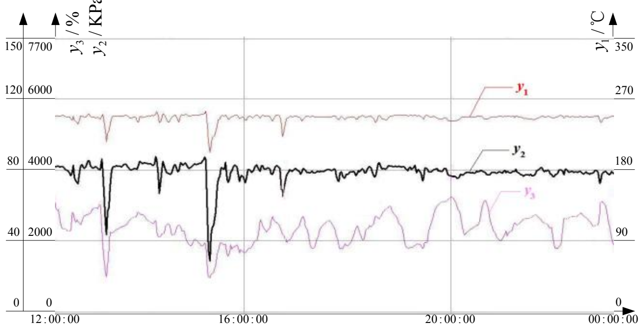

Fig. 6. Technologic parameters history curves of y_1, y_2 and y_3 by adopting the convention PI method

As can be seen from Figure 6, the autoclave inner temperature $y_1(t)$, pressure $y_2(t)$ and level $y_3(t)$ were coupling serious. In 13:00, because of the disturbed, the autoclave inner temperature $y_1(t)$ began to decline, and the traditional PI controller began active, then the autoclave inner pressure $y_2(t)$ began to decline, at the same time, the autoclave inner level $y_3(t)$ began to fluctuate; As can be seen from the whole running curve that since the coupling between variables, and made the output variable continue the ongoing adjustment, The fluctuation ranges of temperature $y_1(t)$, pressure $y_2(t)$ and level $y_3(t)$ of the autoclave that 200 ℃ ~260 ℃ , 2000Kpa~5000Kpa and 30%~60%. Therefore this control method can not effectively control the output variables in the target rages. and then could not get a higher nickel and cobalt leaching rate. As shown in Table 1.

Table 1. Nickel and cobalt leaching rate comparison

Leaching rate	Conventional method	This paper method
$r_1(t)$	90.5%	96.0%
$r_2(t)$	84.5%	95.0%

Using the control method of proposed in this paper, The curve of control is shown in Fig.7, the autoclave inner temperature $y_1(t)$, pressure $y_2(t)$ and level $y_3(t)$ were in steady state. In 17:00, when the disturbances was happened, As the role of nonlinear multivariable decoupling PID controller based on predictive model, and the output variable did not cause a greater impact, During the stable operation process, the temperature of the autoclave y_1 stays at the target value 255℃, the pressure y_2 stays at the target value 4500Kpa and the liquid level y_3 stays at the target value 50%. Significantly improve the efficiency of extraction of nickel and cobalt.

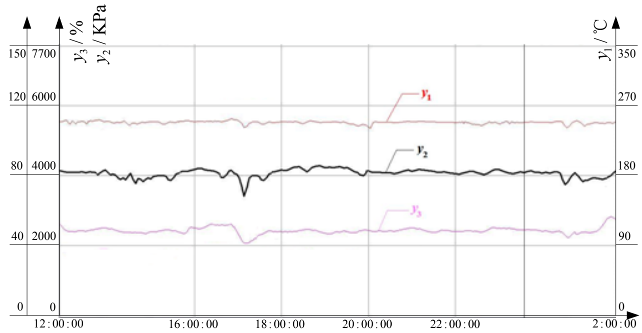

Fig. 7. Technologic parameters history curves of y_1, y_2 and y_3 by adopting the proposed method

The application of this method in practical industrial field indicates the method can keep the temperature, pressure, liquid level at the target value through the nonlinear multivariable decoupling PID control based on predictive model. Meanwhile the leaching rate of nickel and cobalt is about 96.0% and 95.0%.

5. CONCLUSIONS

This paper using nonlinear multivariable decoupling PID control based on predictive model, which consists of the model predictive section and the nonlinear decoupling section. The model predictive section was according to mechanistic models and online correction, combined with nonlinear decoupling PID controller. Industrial application results show that this paper proposed method can the temperature, pressure and level of the autoclave control in the target range, and significantly improve the leaching rate of nickel and cobalt.

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