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Dynamic Control Design and Simulation of Biogas Pressurized Water Scrubbing Process

BO Cuimei*, GUO Wei*, TANG Chao*, LI Jun*, LU Xiaohua**

* *College of Automation and Electrical Engineering, Nanjing Tech University, Nanjing 211816, China (e-mail: lj_bcm@163.com)*

***State Key Laboratory of Materials-oriented Chemical Engineering, Nanjing Tech University, Nanjing 210009,China (e-mail: xhlu@njtech.edu.cn)*

Abstract: For the process of biogas pressurized water scrubbing, design and simulation of plant-level dynamic control system is researched based on the optimum structure and parameters of the steady state in this paper. According to the process requirements of the biogas pressurized water scrubbing pilot-scale plant, a steady state simulation system is established using Aspen Plus. The simulation research under different operation conditions is carried out to obtain the optimal operating parameters. Then plant-level dynamic control schemes and the dynamic simulation system are also designed to ensure the efficiency of biogas purification. The system's performance is tested under introducing biogas inlet flow disturbance and intake flow component disturbance. The simulation results show that the system has good dynamic response performance, such as the removal rate of CO2 is greater than 99.8% under various disturbances.

Key words: Biogas; pressurized water scrubbing; optimal design; plant level dynamic control; Aspen plus

INTRODUCTION

Biogas can be used to replace the traditional natural gas in automotive energy, natural gas pipe network and chemical raw materials etc. The development of biomass energy can realize resource utilization, environmental improvement and optimization of energy structure. Biogas mainly contains biological methane and carbon dioxide[1], and biogas purification technologies become the important part in the development of biogas industry. Several treatment technologies are available for biogas upgrading: pressurized water scrubbing, pressure swing adsorption, membrane separation, chemical absorption, and gas permeation[2-6]. Pressurized water scrubbing is a well-known technology and the most effective upgrading process, since provides a simultaneous removal of CO_2 and H_2S. The main principle is that CO_2 and H_2S are more soluble in water compared with CH_4[7].

Many experts and scholars have studied the pressurized water scrubbing which removes CO_2 in biogas. Liu Xiao-rui etc.(2015)[8] used Aspen software to simulate the technology of MDEA removing carbon dioxide from the biogas, and have obtained the best parameters of temperature, liquid gas ratio and the concentration of absorption liquid. Cozma etc.(2014)[9] have simulated the process of water scrubbing purification and analyzed the effect of liquid gas ratio, absorption pressure, absorption temperature on purifying. Gotz etc.(2011)[10] have used pressurized water scrubbing technology to simulate the process which biogas flow rate is 242.3 Nm^3/h, and carried on the detailed analysis of the purification result. Most studies of biogas pressurized water scrubbing process are based on steady state and few literatures report dynamic control of pressurized water scrubbing.

Based on biogas pressurized water scrubbing process, plant-level control scheme design and dynamic simulation study are carried out in this paper. First, the commercial software tool Aspen Plus was applied to establish the steady state simulation system according to the real pilot experimental device; then the plant-level control scheme and dynamic simulation are researched to realize the dynamic simulation system of control scheme; finally, the dynamic performance of control system are tested by introducing ±10% methane gas inlet flow disturbance and improving the system load disturbance.

1. PRESSURIZED WATER SCRUBBING PROCESS

1.1 Technological process

As is shown in Fig.1, Pressurized water purification process mainly includes five steps: pressurized process (COM_1-COM_3), heat exchange process (E_1-E_3), absorption column (C_1), flash column (C_4) and desorption column (C_2).

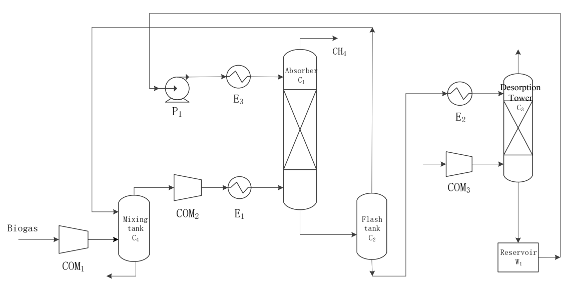


Fig.1 Flow sheet of pressurized water scrubbing

Original incoming biogas is pressurized to 0.9-1.2 MPa before entering the absorption column C_1, absorbing liquid is entering from the top, in the process of biogas upward flow, CO_2 and H_2S are dissolved in the absorption liquid. The enriched CH_4 is collected at the top, and the rich liquid (liquid absorbed CO_2 and H_2S) flows from the bottom. During the whole process, pressurized water scrubbing is a totally physical absorption process and needs no chemicals[11],while the disadvantage is a large amount of water consumed. At present, the study of pressurized water scrubbing is mainly concentrated in reducing water consumption and pressure[12]. By Henry's law[13], the relationship between component pressure and gas composition concentration is:

$$p_B = kx_B \tag{1}$$

In formula (1), x_B is liquid phase mole fraction of gas composition, k is Henry coefficient, p_B is equilibrium partial pressure of gas composition in the gas phase. Different gases under the same pressure, the Henry coefficient is smaller while its solubility is greater according to formula(1). Under the condition of temperature ranging from 0℃to 30℃, Henry coefficient of CH_4 is 25 to 30 times compared with CO_2 in water. Which means the solubility of CO_2 is much higher than CH_4 in water, so water can be used as absorbent to absorb CO_2 in the biogas.

1.2 Establish steady state simulation system

In this section, the commercial software tool Aspen Plus was applied to establish the steady-state simulation system. Simulation system mainly includes the establishment of pressurization process, heat exchange process, flash vaporization process, absorption process, desorption process, mixing process, and the steady state simulation and optimization of the whole process.
A brief analysis of simulation results regarding the available literature data was developed. The simulation results in this paper are basically the same compared with literature in table1. Therefore, the steady state model established in this paper is relatively reliable.

Table1 Comparison of simulation results

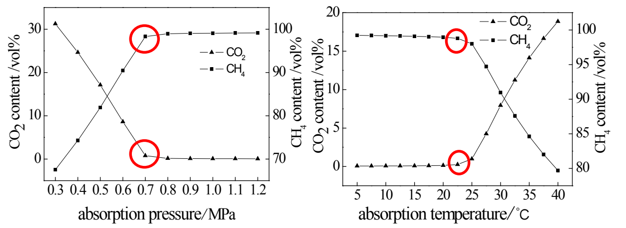
parameter	Units	Results of Cozma et al.	Results of this paper
CH_4/CO_2	vol%	53.7/45.2	53.7/45.2
H_2S/H_2	ppm	100/-	101.8/-
$N_2/O_2/H_2/H_2O$	vol%	0.93/0.19/0.05/-	0.93/0.19/-/1.67
$P_{absorber}$	bar	8	8
Temperature	℃	20	20
Make-up water (WFR)	kg/h	-	488
P_{flash}	bar	3	3
$P_{stripper}$	bar	1	1
Upgraded biogas	mole fraction		
CO_2		0.965	0.968
CH_4		0.00397	0.002
H_2S		0.000094ppm	0. 955ppm
N_2		0.00319	0.003
O_2		0.0209	0.021
H_2		0.00563	0.006
H_2O		0.000902	
Off gas	mole fraction		
CO_2		0.000677	0.000926
CH_4		0.171	0.169
H_2S		38ppm	38ppm
N_2		0.0234	0.023
O_2		0.635	0.638
H_2		0.168	0.169
H_2O		0.193	

1.3 Optimum process Structure and Parameters

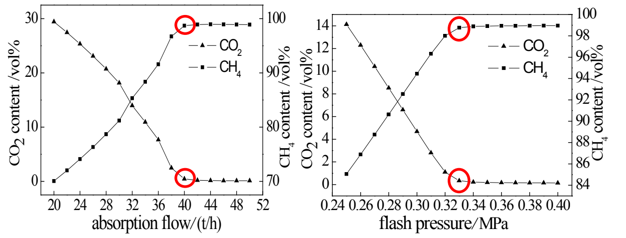
To seek the optimum operating parameters for the real pilot experimental device, steady state simulation under different operation conditions is carried out. The methane purifying effect (CO_2 removal rate) is analyzed under different operating conditions, which include different absorption pressure, absorption temperature, absorption liquid flow and gas flow etc. Purification effect is represented by carbon dioxide removal rate, the formula is as follows:

$$\Phi(\%) = \frac{\varphi_{in} - \varphi_{out}}{\varphi_{in}} \times 100\% \tag{2}$$

In formula(2), Φ, φ_{in} φ_{out} represents CO_2 removal rate, biogas original volume fraction of CO_2, product gas CO_2 volume fraction respectively.
Fig.2(a)-(d) represents the impact on purifying effect of absorption pressure (0.3-1.2MPa), absorption temperature (5-40 ℃), liquid gas ratio (absorbent flow into the absorption tower with biogas inlet flow), and flash pressure(0.2 MPa-0.4 MPa).



(a) Influence of absorption pressure (b) Influence of absorption temperature



(c) Influence of absorption flow (d) Influence of flash pressure

Fig.2 Influence of different operation parameters on purification effect

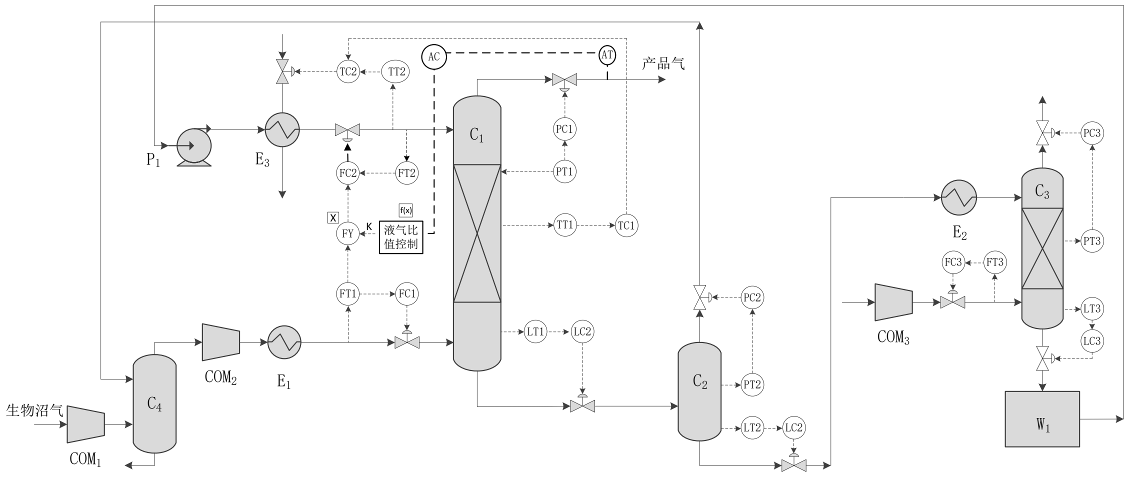


Fig. 3 Flow sheet of dynamic simulation of supervisory control scheme

It can be seen from the simulation results that the CO_2 removal rate is higher and the content of CH_4 in the product gas meet the process requirements while the absorption pressure is 0.7 MPa, the operating temperature is 20 ℃, liquid gas ratio is 115, flash vaporization pressure is 0.33 MPa..

2. PLANT-LEVEL DYNAMIC CONTROL SCHEME

The purification process of biogas pressurized water scrubbing is relatively complex, the appropriate process control schemes are designed in this section to ensure the effect of biogas purifying based on the optimal structure of biogas pressurized water scrubbing process.

Multivariate control scheme is designed in Fig.3 according to the dynamic analysis. The control loops of absorption column(C_1) mainly includes absorbent flow rate loop, liquid level loop, absorption pressure loop and absorption temperature loop, the control of absorption column directly affect the quality of product gas.

Table 2 Multivariable control and control parameters

equipment unit	control scheme	controller	parameters Kp	Ti（min）
Absorber C_1	Ratio control of Feed rate	FC1	3.2	1.32
	Forward-feedback control of level	LC1	12.56	1.98
	PID control	PC1	2	12
	Cascade control	TC1	0.8	5.28
Flash Tank C_2	PID control	LC2	3.29	3.96
	PID control	PC2	20	12
Desorption Tower C_3	PID control	FC3	6	3.89
	PID control	PC3	6.27	1.32
	PID control	LC3	202.95	3.96

We find the main factors influencing the flash tank (C_2) pressure are liquid inlet flow, liquid outlet flow and gas outlet flow by analysis. A pressure control loop and a liquid level control loop are designed for the flash tank.

For desorption column (C_3), the air inlet flow has a great influence on the purification process. So the control loop of air inlet flow rate is designed, desorption pressure and liquid level which are shown in table 2.

3. DYNAMIC SIMULATION SYSTEM

The Aspen Dynamics modules are added to the Aspen Plus steady state simulation system, and the above plant-level control scheme are applied to establish the dynamic process simulation system and the dynamic performance of the control scheme is tested.

3.1 Establishment of dynamic simulation system

To test the effectiveness of the proposed control scheme, a dynamic simulation system was established in this section based on Aspen Plus steady-state simulation in Fig.4. In dynamic simulation system, the controller parameters are tuned based on relay feedback test combine with Tyreus-Luyben tuning method. The main controller parameters are shown in table 2.

After 5 hours steady running with no disturbance, the dynamic performance is tested and analysis of the system are carried out. The intake volume ±10% disturbance is tested, the intake volume component disturbance is tested, system tracking ability also is tested to verify the performance of closed-loop control system.

3.2 Stability test under disturbance±10% of biogas intake flow

After 1 hour steady running of the system, ± 10% biogas intake disturbance is added. Dynamic response simulation results of biogas intake flow rate, absorber flow rate, liquid level, absorption temperature, absorption pressure and the CO_2 removal rate are

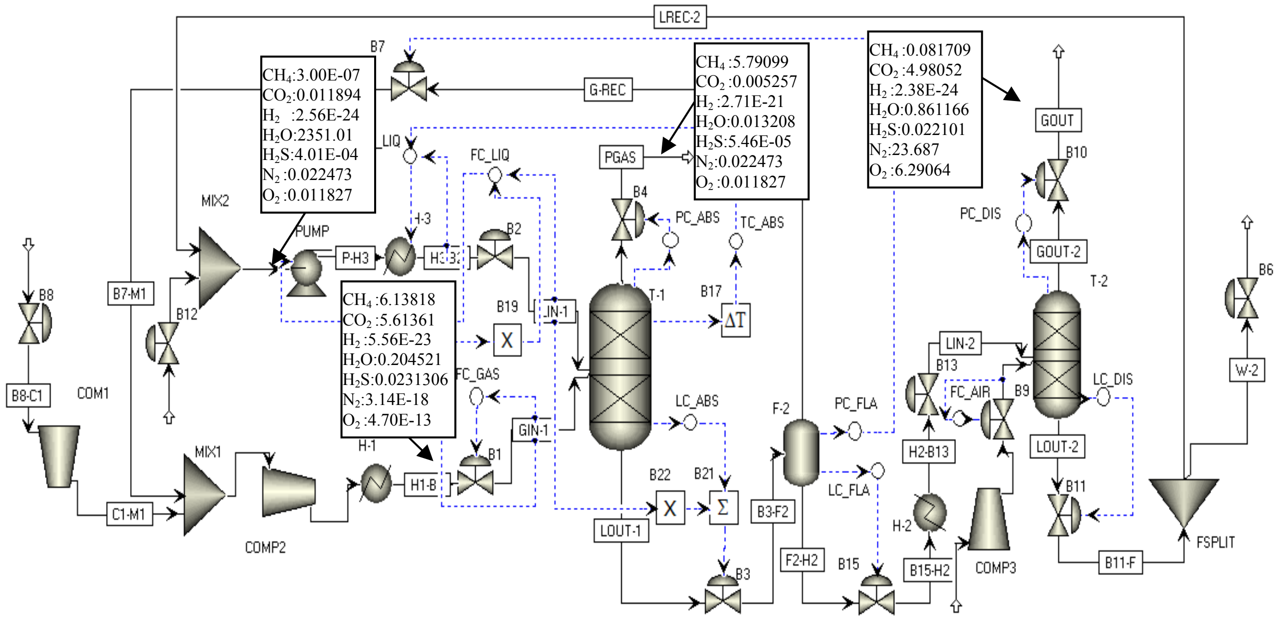


Fig. 4 Flow sheet of dynamic simulation of supervisory control scheme

shown in Fig.5.

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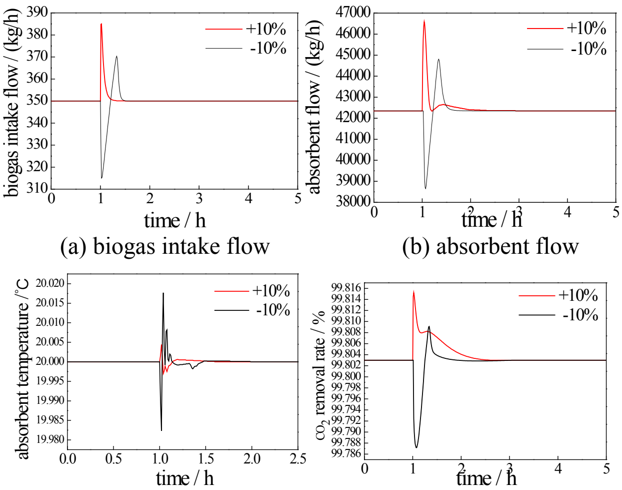


(a) biogas intake flow (b) absorbent flow

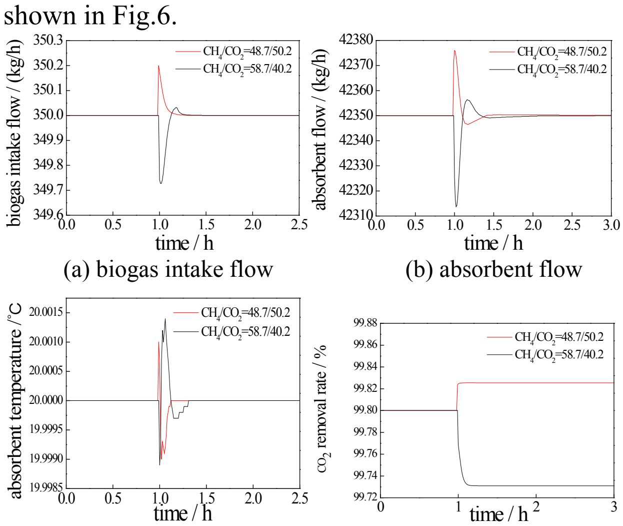
(c) absorbent temperature (d)CO_2 removal rate

Fig.5 Dynamic response curve with ±10% biogas flow disturbance

Taking the +10% disturbance of intake biogas flow as an example, Fig.5(a)(b) represent the dynamic response of feed flow and absorbent flow respectively, according to the chart, absorbent flow is proportional to the change of gas flow under the effect of double closed-loop ratio control, the two flow quickly return to the steady state value after the disturbance disappear. In the Fig.5(c), the temperature of absorption column becoming higher because of the increase of biogas inflow, though the absorption temperature is volatile, the temperature value is 20 ℃ with no disturbance after 0.7 hours through the cascade control scheme designed. In Fig.5(d), the disturbance makes absorbent flow rate increase and the absorption tower pressure higher; these changes are conducive to the CO_2 removal. Under the control of designed scheme, the CO_2 removal rate is also restored when process parameters are reset to the value.

3.3 Stability test under disturbance ±5% of biogas intake component

After 1 hour steady running of the system, biogas intake component disturbance is added .The content of CH_4 is 48.7%, and the volume fraction of CO_2 is adjusted from 45.2% to 50.2%. Dynamic response simulation results of biogas intake flow rate, absorber flow rate, liquid level, absorption temperature, absorption pressure and the CO_2 removal rate are shown in Fig.6.



(a) biogas intake flow (b) absorbent flow

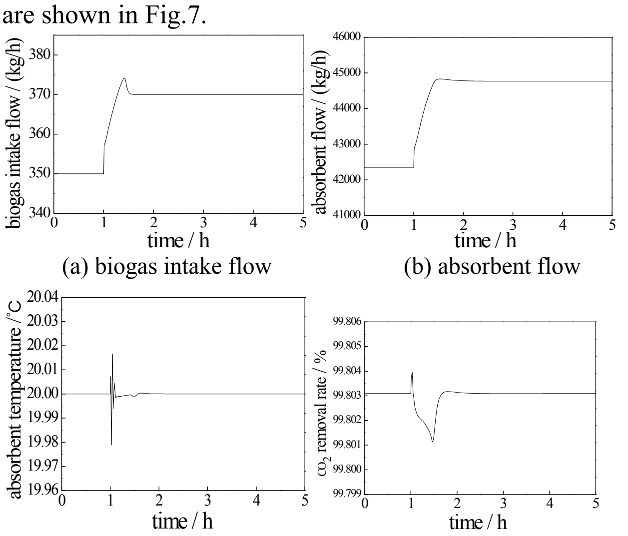
(c) absorbent temperature (d) CO_2 removal rate

Fig.6 Dynamic response curve with biogas under intake component disturbance

As is shown in Fig.6(a)(b), there is a slight fluctuation in the intake flow with the influence of biogas intake component change, and absorbent flow changes in proportion with biogas flow at the same time. As is showed in Fig.6(c), there remains time delay in change of temperature. Take CH_4/CO_2=48.7/50.2 as example, the increase in biogas intake flow leads to the temperature increase in absorber column, and it can be adjusted quickly to set point 20℃ by the application of cascade control strategy. It can be known from Fig.6(d) that as the proportion of CO_2 increases in biogas, the removal rate of CO_2 increases too. However, the increase in the proportion of CO_2 in biogas also leads to the decrease in CH_4 concentration in production.

3.4 Tracking performance test

After 1 hours steady running of the system, the intake gas flow setting value is increased from 350kg/h to 370kg/h, 5 hours later, the dynamic response simulation results of biogas inlet flow rate, absorber flow, absorption temperature, absorption pressure and CO_2 removal rate are shown in Fig.7.



(a) biogas intake flow (b) absorbent flow

(c) absorbent temperature (d) CO_2 removal rate

Fig.7 Dynamic response curve after lifting system load

As is shown in Fig.7(a)(b), under the effect of double closed loop ratio control, the intake biogas flow can track the set value quickly, when intake biogas flow rate setting is increased from 350 kg/h to 370 kg/h. Absorbent flow rate also increase due to the increase of gas inlet flow rate. The sudden increase air inflow rate makes the increase of both biogas and absorbent intake flow, which results in the increase of absorption pressure and temperature. From the simulation results, the designed control scheme is effective for both system load improvement and parameters disturbance, each process parameters have rapidly restored to the set value, meanwhile, the change of CO_2 removal rate is smaller, and the quality of products gas meets the requirement.

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4. EXPERIMENTAL RESEARCH

Experiments are carried out on the automatic control device of biogas pressurized water scrubbing purification, and the experimental results are analyzed in this section.

4.1 Pilot experimental device

According to the 973 project, our school has developed a pilot experimental device for biogas pressurized water scrubbing purification process. In order to guarantee the safety, experiments were conducted using N_2 instead of CH_4. The experimental gas consists of 55% N_2 and 45% CO_2. Experiment equipment is shown in Fig.8.

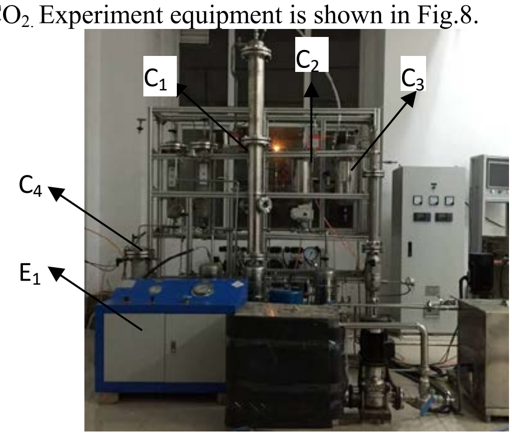

Fig.8 Pilot experiment device

4.2 Design and implementation of automatic control system

The design of control program includes hardware configuration, input signal reading and control scheme realization based on SIEMENS S7-200 SMART controller. In the process of control, analog inputs or output control is included, so it is necessary to add analog input expansion module and analog output expansion module.

The SIEMENS configuration software WinCC is used to develop the process monitoring system. As shown in Fig.9, the process flowchart and process variables are displayed.

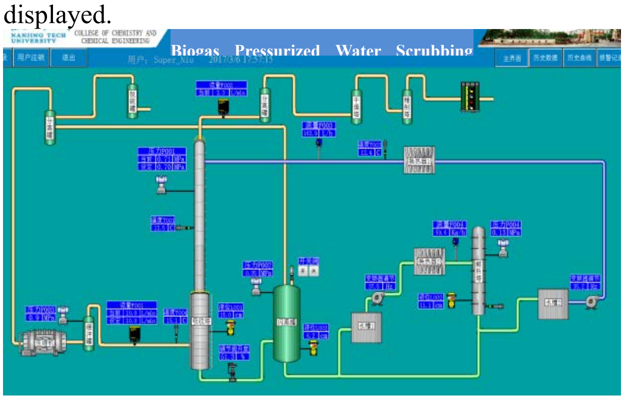
Fig.9 Process monitoring system on WINCC

In SIEMENS S7-200 SMART programming software

STEP7, control scheme designed in section 2.2 is implemented, and the program is downloaded to PLC to control the process and ensure the smooth operation of the equipment. Process parameters such as liquid-gas ratio, absorption pressure and absorption temperature were experimented in designed equipment. The set points of experimental parameters are as follows: the absorption pressure is 0.7 MPa, liquid-gas ratio is 180, the absorption temperature is 12 °C, the flash pressure is 0.35 MPa, and the desorption pressure is 0.1 MPa. Part of the parameters charts during the operation of the device is shown in Fig.10.

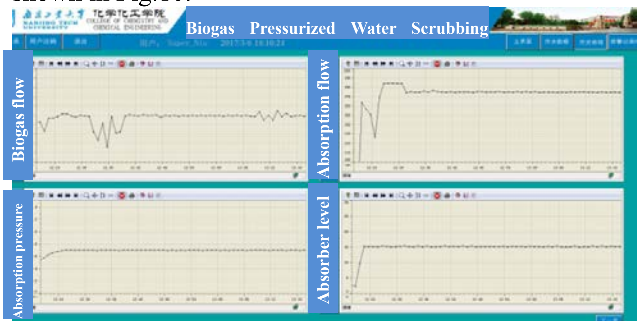

Fig.10 Curves of device operation process parameters

Fig.10 shows, the controlled variables are stable at set point, and the control system has the ability to overcome disturbances. After steady running of the system, the CO_2 content in the product gas is less than 1.7%, which conforms to the standard that the CO_2 content of the compressed natural gas should be less than 3% .

5. CONCLUSION

In this paper, we have studied the pressurized water scrubbing treatment technologies of biogas purification, based on the analysis of process dynamic response characteristics; process control scheme was designed according to the process characteristics. Simulation results show the plant-level control scheme can effectively restrain disturbance of the biogas inlet flow, and ensure the control quality of process. The biogas flow rate can quickly track the set value when the system load and biogas inlet flow rate are both increased. The automatic control system of the experimental device is also developed to ensure the efficient and smooth operation of the device.

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