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Study on Spiral Tube Compound Gas-liquid Separator with Fuzzy PID Control

Guomin Xue[1] and Yi Shen[1]
[1]Control Science and Engineering Department, Harbin Institute of Techology, Harbin, 0451-86418378

Abstract
A new kind of spiral tube compound gas-liquid separator is designed basing on the analysis of gravity and centrifugal force effect on fluid in spiral tube. The numerical simulating validates the design of the structure of the spiral tube separator is good. With the comparison of three control plans, the plan to keep liquid level stably through controlling gas exit out flux is chose. The manual and the automatic experiments prove it is feasible. Fuzzy-PID controller is designed according to Ziegler-Nichols step response method and manual experiences. Experiments show that the fuzzy-PID controller has excellent anti-jamming performance. Experiments on oil-gas-water separation prove that the separator is three times as efficient as the same size gravity separator in practical separation.

Keywords - spiral tube, gas-liquid separator, fuzzy, PID, control

1. INTRODUCTION

Gas-liquid separator can be classified into three types: gravity, centrifugal and compound separators based on the mechanics principle (Shuchu Feng, Kuichang Guo, Wang xuemin.1988). For separating the same amount of oil and gas, the gravity separator are usually big in size while the centrifugal separators are often small (Jinsong Zhang, Yong Zhao, Shuchu Feng. 2002). Therefore, it is important to create a kind of gas-liquid separators which are small in size and efficient in performance. With less occupied area and less investment and high efficiency, this kind of new separators can be used on offshore platforms or used for metering of individual wells(Xuewen Cao, Jie Kou, Zonghu Lin.2003). So far, many kinds of compound separators have been developed in China and foreign countries by some research organizations or manufacturers. It includes column-cavity separator, single cone-cavity separator, cyclone board separator and rectangle spiral channel separator, etc (Kou Jie, Chunsheng Liu, Zhusheng Wang.2002). Yuejin wang elucidates various kinds of applications status of hydrocyclonic separation technology in petroleum industry, including degassing, dewatering, desanding, deoiling of oily water(Wang Yuejin, Yuan Huixin, Zhao Xiaomei.2003). Liu Xiaomin designs a cone gas-liquid hydrocyclone, and the test experiments show that the hydrocyclone is feasibility for gas-liquid separation with small size, light weight and easy operation (Liu xiaomin, Jiang Minghu, Zhao Lixin.2004). Zhou Yong's researches on oil-water separation with numerical simulation in both straight and helical pipes give clear result pictures of separating, and the separator's structure can be designed according to the results(Zhou Yong, Wu Yingxiang.2004). Now there are two technical problems still challenging the separator designers. One is how to keep the separator's pressure and liquid level stable. Another is how to reduce its size and improve its efficiency. A new design of a compound gas-liquid separator with spiral tube and fuzzy-PID control is presented in this essay. The related test results are also provided.

2. ANALYSIS ON GRAVITY AND CENTRIFUGAL EFFECT IN THE SPIRAL TUBE

Figure 1 shows the shape of a spiral tube. Centrifugal force is produced when fluid flows in the spiral tube. Figure 2 shows the forces and traveling track of a liquid drop.

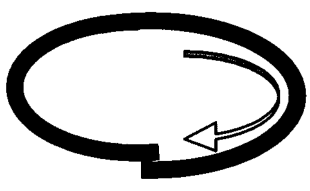

Figure 1. Shape of a spiral tube

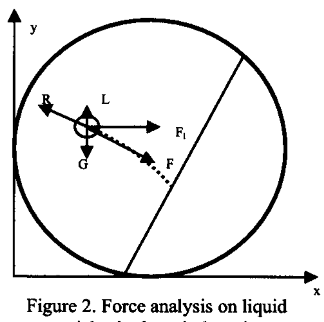

Figure 2. Force analysis on liquid particles in the spiral section

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Forces on the liquid drops include gravity G, centrifugal Fl, gas flotage L and gas resistance R. Resulting force F can be calculated by the following formula

$$F = \frac{\pi d^3}{6}\left\{\left[\left(\rho_l - \rho_g\right)g\right]^2 + \left[\frac{32\rho_l q^2}{\pi^2 D_1^4 D_2}\right]^2\right\}^{1/2} \quad (1)$$

In formula

d —diameter of the liquid drops, m;

ρ_l, ρ_g —liquid drop and gas density in separating condition, kg/m3;

g— gravity acceleration, m/s2;

q— total volume of oil and gas, m3/s;

D1— diameter of the spiral tube section, m;

D2— diameter of the spiral tube cycle, m.

Gas resistance R can be calculated by the following formula:

$$R = \xi \frac{\pi d^2}{4} \frac{\omega^2}{2} \rho_g \quad (2)$$

In formula

ξ —resistance modulus;

ω —movement velocity of liquid drops in the spiral tube section, m/s。

Liquid drops can be separated from gas in the spiral tube in such condition that the time of the liquid drops moving to the gas-liquid interface is shorter than the time of the mixture moving along the spiral tube. Centrifugal force on gas bubbles is

$$F_g = m_g a = \rho_g V_g a \quad (3)$$

In formula

m_g—quality of bubble, kg;

ρ_g—density of bubble, kg /m3;

V_g—volume of bubble, m3;

a —acceleration of centrifugal force, m/s^2.

The principle of bubbles separating from liquid is same as the principle of liquid particles separating from gas. Bubbles float to liquid surface with the resulting force of liquid flotage, gravity, centrifugal force and liquid resistance. Because the viscosity of oil is big, the float up-velocity is slow, the Renult Parameter is small, the flow is laminar flow. The uniform float up-velocity of bubble can be calculated by Stokes formula

$$\omega_g = \frac{d_g^2 a_h \left(\rho_l - \rho_g\right)}{18\mu_l} \quad (4)$$

In formula

ω_g—uniform float up-velocity of bubble, m/s;

d_g—diameter of bubble, m;

a_h—bubble acceleration caused by gravity and centrifugal force, m/s^2;

u_l—dynamical viscosity of oil on separating conduction, Pa•S.

Gas bubbles can be separated from liquid under the condition that the time of the gas bubbles moving to the gas-liquid interface is shorter than the time of the mixture moving along the spiral tube. The time of the gas bubbles moving to the gas-liquid interface can be calculated by the formula

$$t_g = \frac{D_1}{\omega_g} \quad (5)$$

The time of the mixture moving along the spiral tube can be calculated by the formula

$$t = \frac{n \cdot \pi D_2}{\frac{q}{\pi D_1^2}} \quad (6)$$

To take t_g equal to t, there is

$$\omega_g = \frac{q}{\pi^2 n D_1 D_2} \tag{7}$$

3. DESIGN AND NUMERICAL SIMULATION OF THE SPIRAL TUBE SEPARATOR

3.1. Design of the separator

The purpose of this work is to design a small and high efficient separator. A spiral tube can help to increase separating efficiency. So a separator with gravity separating cylinder and spiral tube is designed, just as figure 3 shows. It includes gas gathering cylinder,liquid gathering cylinder and spiral tube cylinder. Gas gathering cylinder is a cavum with a mist catcher at the outlet. Liquid gathering cylinder is also a cavum with a vortex baffle at liquid outlet. The spiral tube separating cylinder is composed of an outer body and a multi-circle spiral tube. Holes are drilled on inner upside and outer underside of the spiral tube. The separated gas comes out from inner bores, and the separated liquid comes out from the outer bores. When gas comes into the gas gathering cylinder, the left liquid drops fall down on the effect of gravity. When liquid comes into the liquid gathering cylinder, the left gas bubbles rise up under the force of buoyancy. The separator parameters include column diameter, height of gas cavity, diameter of spiral tube section, diameter of spiral tube, amount and diameter of the bores, number of spiral tube circles, distance of the circles, height of liquid cavity, diameter of oil and gas discharging tubes. The structure parameters can be calculated according to the hydrodynamics principle(G. V. chIlingarain, Zhaobin Huang. 1995; Chuanzhai Chen.2003). The sizes of the main parts of the test separator are designed according to gravity effect principle with maximum liquid flux burthen 50 m^3/d and gas flux 150 m^3/d . The pressure is 0.4MPa. The centrifugal acceleration is $30m/s^2$. Calculation shows that the column diameter is 300mm, with the full height 150mm, height of liquid gathering cylinder 800mm, height of spiral separating cavity 400mm, spiral tube section diameter 25mm, bore diameter 3mm, circle number 9. For purpose of convenient observation and analysis, the test separator is made of transparent materials.

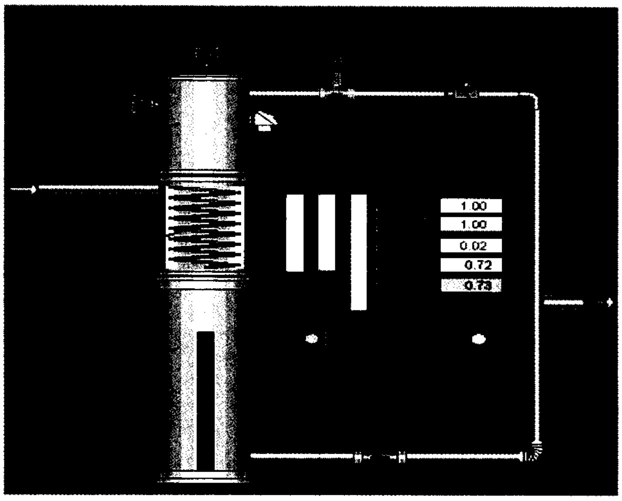
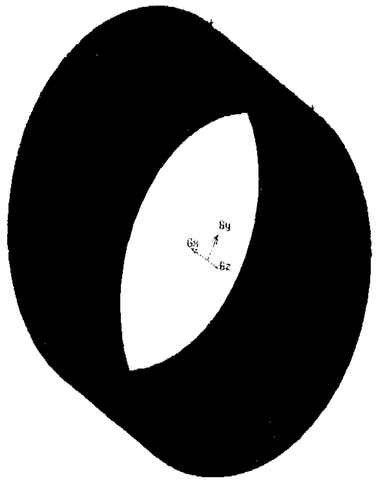


Figure 3. Structure of the separator
(1.gas gather cylinder; 2.spiral tube separating cylinder; 3.liquid gathering cylinder; 4.gas meter; 5.valve for adjustment; 6.liquid flowmeter)

3.2. Numerical simulation of the separator

The numerical simulating is based on the size of the test separator with FLUNENT software. In order to study the flow state, the preceding dealing software is used for modeling of the spiral tube, and compartmentalizing it's reseau. The reseau is subdivising part in order to assure the calculating precision and saving computor's resources. The reseaus of the holes on the spiral tube is tag body reseau. The final amount of reseaus is 942000. Figure 4 shows the multi-cycle structure of the spiral tube. Figure 5 shows the reseaus of the spiral tube and the hole on it. The Eulerian model of multi-phase flow is adopted from the FLUNENT software to simulate the real flow. In the Eulerian model of multi-phase flow, the pressures from all directions are same, the momentum equations and continuity equations of each phase are calculated by oneself. The equations of resistance coefficients can be adopted differently when the phases are different. The model of RNG K-ε is adopted to calculate the turbulent flow parameters. The Phase Couple SIMPLE method for the relative of pressure and velocity is chose for calculating separating parameters. According to the locale condition, the phase nature parameters are as follow. Density of oil is $860kg/m^3$, mucosity of oil is 0.05kg/m·s, density of water is 998kg/m3, mucosity of water is 0.01kg/m·s, density of gas is 1.225 kg/m^3, mucosity of gas is 1.79×10^{-5} kg/m·s. The operation condition is that the operation pressure is 101325Pa, acceleration of gravity is $9.81m/s^2$, the entry flow velocity of mixture is 4m/s, the gas volume content rate of the mixture is 80%. When the mixture is flowing along the spiral tube, the gas and oil will separate with each other on the effect of gravity and centrifugal force.

Figure 4. The multi-cycle structure of the spiral tube



Firure 5. The reseaus of the spiral tube and the holes

Figure 6 shows the separating nephogram of the two phases of oil-gas. Figure 7 shows the separating nephogram of the three phases of oil-water-gas. There are nine cycles of spiral tube. The nephogram is get from tube sections of different cycles. The red is gas, the blue is liquid. The figure shows the gas position and liquid position and the gas-liquid interface transition clearly.

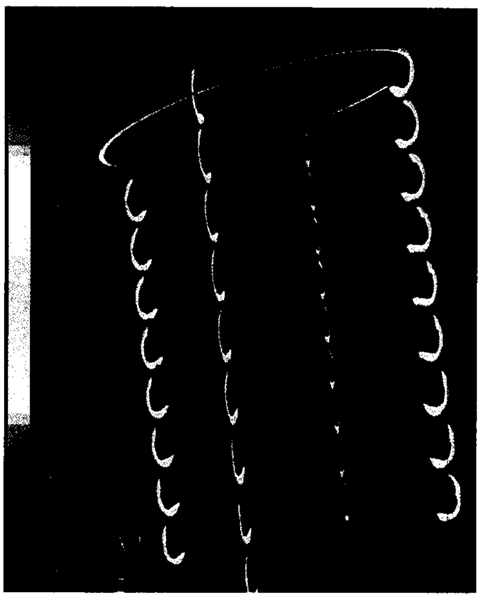


Figure 6. The separating nephogram of oil and gas

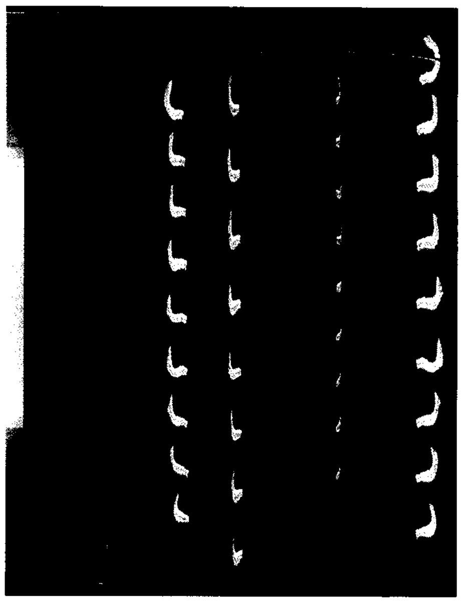


Figure 7. The separating nephogram of oil water and gas

Figure 8 shows the liquid volume content rate nephograms of the mixture in the sixth cycle of spiral tube section. The diameter of the tube cycles is 300mm.

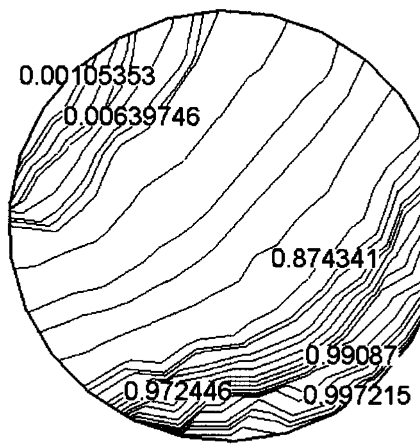


Figure 8. The liquid content rate on the tube section

The separating nephograms show that gas is gathering to the inner upside of the spiral tube, liquid is gathering to the outer downside of the spiral tube. The gas content rate of the mixture is more and more along the inner upside, the liquid content rate of the miture is less and less. This simulating results shows that the separating state is same as that being analyzed initially. The results prove it is right that the holes for gas exit are opened at inner upside 45^0 and the holes for liquid exit are opened at outer downside 45^0. Because the fact output liquid mixture is not even, there are sect part flows when the fluid comes into the beginning cycles of spiral tube. So the 1-3 cycles of the spiral tube is not opened holes. This three cycles of no holes can keep the acceleration large enough to remove the sect part flow efficiently. Holes are opened at the 4-9 cycles on the inner upside of the tube for the separated gas flowing out. Holes are opened at the 6-9 cycles on the outer downside of the tube for the separated liquid flowing out from the holes.

4. DESIGN AND EXPERIMENTS OF THE FUZZY PID CONTROLLER

4.1. Selection of control plans

After the gas liquid mixture enters into the separator from the entrance, separated gas and liquid gather in the separator, the liquid level and pressure come into being. When the system of level and pressure is stable, the out flux of gas exit and liquid exit is equal to the afflux of the entrance. At this time, the separator can run well. The aim of control is to keep the level of liquid at proper position and to keep the different pressure between the body and outlet of the separator at a proper range. So the controlled parameters are pressure and liquid level. The operation parameter is gas and liquid outlet flux. According to the characteristic of the system, there are three control plans for selection. The first plan is to control pressure and liquid level as two separated loops, each loop is a single loop control system. The second plan is to control pressure and level as a multi-in and out system , considering the coupling connection between pressure and level. This plan bases on the model of the multi-in and out system must be get clearly. The third plan is to keep liquid level stably through controlling flux of gas exit. In this plan, the controlled parameter is liquid level and the operation parameter is gas exit out flux. When the gas exit out flux changes, the different pressure between the body of the separator and the liquid exit flux will change too. So the out flux of liquid exit will increase or decrease. At last, the liquid level will be controlled. Table 1 gives the comparison of the three plans. It includes the methods of modeling, the hard ware devices, the control loops and the maneuverability. Through the comparison, we know the third plan is best for modeling, with few devices, single loop and good maneuverability. So the third plan is chosen. In this control plan, the valve for adjustment is set on the pipe of gas exit. The valve will be closed gradually for adjust when the liquid level is higher than the expected value. When liquid level is lower, the valve will be opened gradually.

Table 1. Comparison of control plans

Plan	Methods of modeling	Hard ware devices	Control loops	Maneuver-ability
The First	Response or mathematics	Two valves	Two loops	Common
The Second	Mathematics	Two valves	Two loops	Bed
The Third	Response	One valve	One loop	Good

4.2. Experiments on self stability response

According to the structure and the principle of the separator, the separator has the self stability in a certain range of flow burthen at the condition of the exit collection pipe being higher than the liquid level. The fact fluid experiments have been done to validate the self stability of the separator in the multi-phase lab of Daqing Oil Field China.

Firstly, the small burden startup experiment were done. The provided liquid flux is 20 m^3/d and the gas flux is 85 m^3/d. When the gas-liquid mixure comes into the separator, the gas outlet and liquid outlet keep opening wholly. Figure 10 shows the startup response curves. In this and the following figures, curve 1 shows the liquid level of the separator; curve 2 shows the gas flux of the gas exit pipe; curve 3 shows the pressure of the separator, curve 4 shows the liquid flux of the liquid exit pipe. Figure 10 shows that the pressure increases firstly after the mixture entering, the liquid level increases to 0.72m from zero quickly, and then the level decreases slowly to the stable point 0.67m. The pressure of the separator is stable after the level is not change. And then the out fluxes of gas exit and liquid exit are not change with the level and pressure being stable.

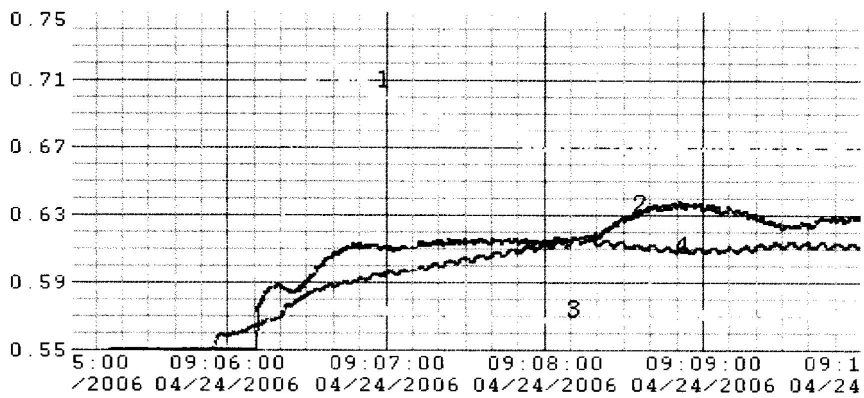


Figure 10. Startup response curves

After that, the burthen change experiments are done. Figure 11 shows the response curves of the burthen change. To keep the provided gas flux 200 m^3/d not change, provided liquid flux increases from 25 m^3/d to 40 m^3/d. Figure 11 shows that the liquid level rises up quickly and largely when the provided liquid flux increasing, it rises from 0.87m up to 1.2m.

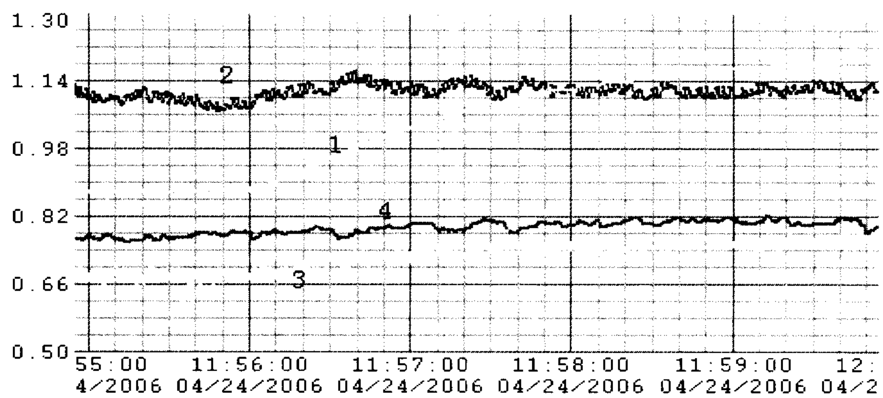


Figure11. Burthen change response curves

The self stability experiment curves show that the separator has self stability in certain flux burthen range, the stable point is different with the different burthen. But the separator's stable liquid level will higher than permitted value when the gas flux burthen is small or liquid burthen is big, it is necessary to set a automatic valve on gas exit pipe to adjust the liquid level.

4.3. Open-loop response experiments

Figure 12 shows the control system frame. The open loop process is combined with adjusted valve, gas flow meter and liquid level meter. The system model can be get through the open loop step response curves. Manual setting experiments are performed firstly to prove the feasibility of the third plan. During the experiments, the classical provided liquid flux is 66m^3/d and the provided gas flux is 200m^3/d. The liquid valves are opened completely at all time. Only the gas valve is used to adjust the gas flux of gas exit pipe in order to keep the liquid level stable. The result of manual experiments shows that liquid level can be controlled effectively by this way. The ideal result of the manual setting experiments leads to design the controller as fuzzy-PID controller finally. Then the open-loop response experiments are carried out to determine process parameters of the system. In the experiments, the gas valve is adjusted manually to keep the liquid level being stable firstly, then the gas valve is adjusted quickly to another position. The change of liquid level is recorded. Figure 13 shows the step response curves. The response curves in figure 13 shows that the separating system is a delay integral unstable process. In fact, the change of the liquid level is a material accumulating process. It accords with the integral principle.

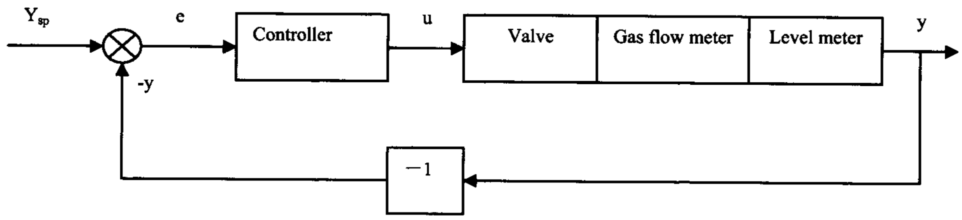


Figure 12. The control system frame

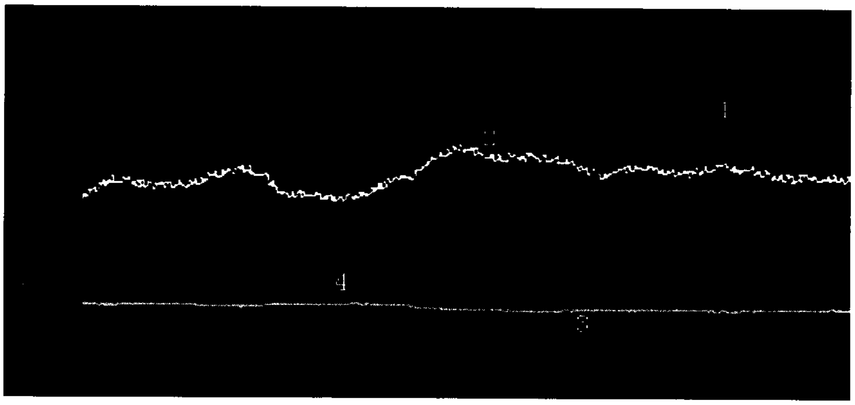


Figure 13. Open-loop response curves

According to the response curves, the transfer function of the open loop is

$$G(s)=\frac{1}{0.4s}e^{-0.4s} \tag{8}$$

4. 4. Design of fuzzy PID controllor

The PID controller is designed according to Ziegler-Nichols step response methods(Astron write,Ren Dexiang translate.1999). The parameters of PID controller can be calculated as the table 2.

Table 2 Formula of parameters calculating for PID controller as Ziegler-Nichols step response method

Type of controller	Plus K	Time of integral T_i	Time of differential coefficient T_d
P	1/a	\	\
PI	0.9/a	3L	\
PID	1.2/a	2L	L/2

Based on Ziegler-Nichols method, the parameters of PID contoller are obtained by calculation, they are K=1.2、T_i=0.8、T_d=0.05. The parameters are adjusted after operation as K=1、T^i=1、T_d=0.02. Then experiments on level set step change are carried out in order to know the performance of controller. The liquid provided flux is 60 m^3/d and gas flux is 200 m^3/d. Figure 14 and 15 show the response curves obtained. The curves show that the closed-loop system is an inertia stable system without any waves when the level set step change rate is 22%. The top excess is <3%. Therefore, the closed-loop system has a stable performance with PID controller for correction, but the time for dynamic response is long.

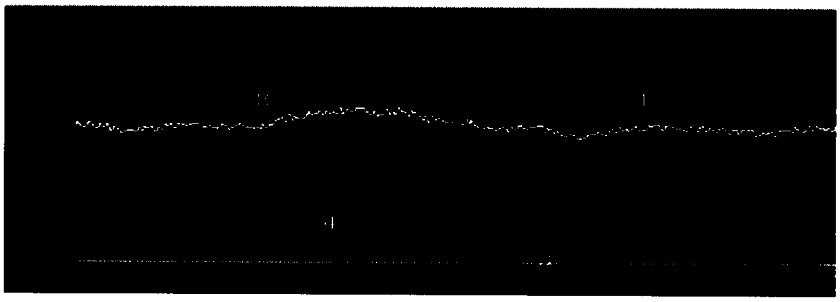


Figure 14. Curves for increased set values of PID controller

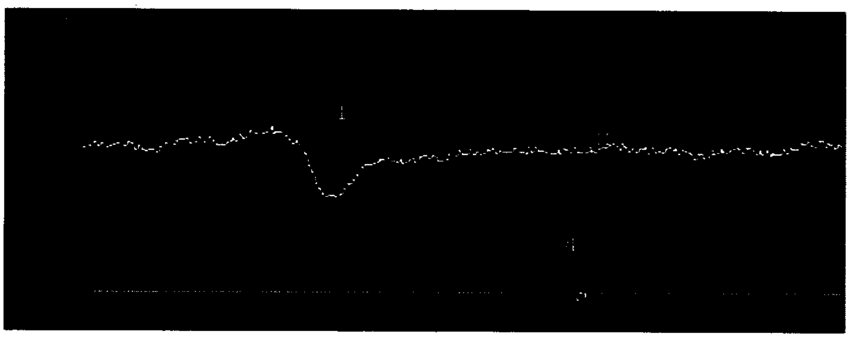


Figure 15. Curves for decreased set values of PID controller

The fuzzy control plan is made in order to improve the dynamic response capability. That is, fuzzy control method is adopted when big errors occur, while PID control method is adopted when errors turn to small. Fuzzy control is based on manual control experiences. When the error is big and the change of error is quick, the adjustment output is big too, so that the dynamic time can be shortened. When the error is small enough, PID control can be used instead of fuzzy plan, so that good and stable features can be achieved. The fuzzy controller is designed as follows: the liquid level fuzzy variable is defined as {NB,NM,ZERO,PM,PB}, the liquid level variety fuzzy variable is defined as {NB,NM,ZERO,PM,PB}, the valve output fuzzy variable is defined as {NB,NM,ZERO,PM,PB}, subject functions are quantified as triangle form(Shiyong Li.1998). Then the experiments on level setting change with fuzzy PID controller are carried out. The response curves are shown in figure 7 and 8. Compared with the curves in figure 5 and 6, the dynamic response time is shorter and the static capability is good too.

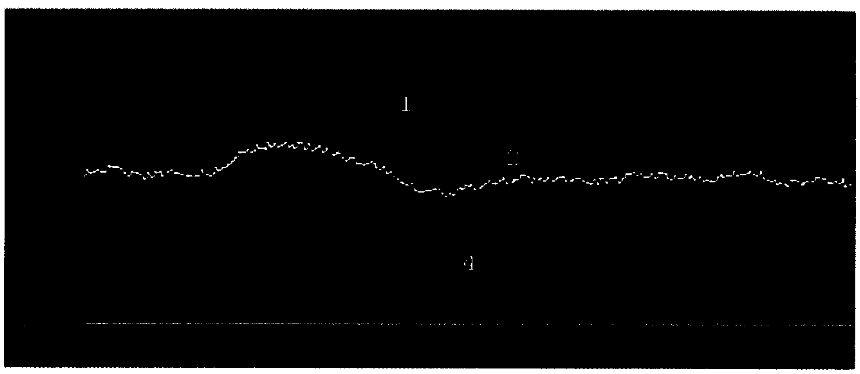


Figure16. Curves for increased set values of fuzzy PID controller

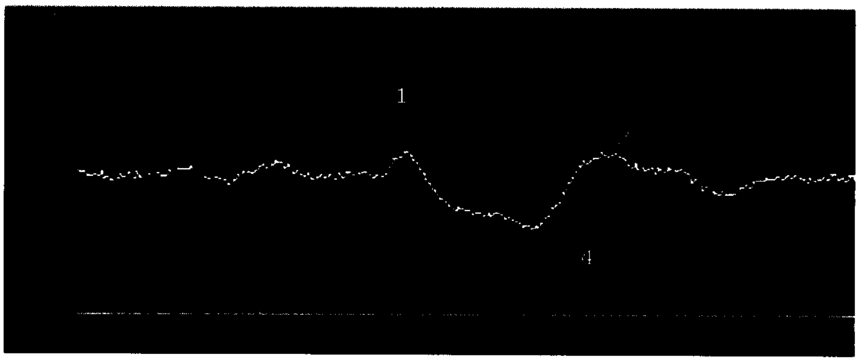


Figure 17. Curves for decreased set values of fuzzy PID controller

4. 5. Load disturbance experiments

The uppermost disturbance in the system operation is the change of flux burthen in the separator. Therefore, close loop experiments on burthen disturbance are carried out. The provided liquid flux is 66 m^3/d and the gas flux is 200 m^3/d. When the system is controlled stably, the gas and liquid flux are both reduced by 30%. And then they are both increased by 50%. Figure 9 and 10 show the response curves of the change of flux burthen. These curves indicate that the closed-loop system responds to the load disturbances quickly, but the liquid level changes within a small range. So the fuzzy PID control system is good in anti-jamming performance.

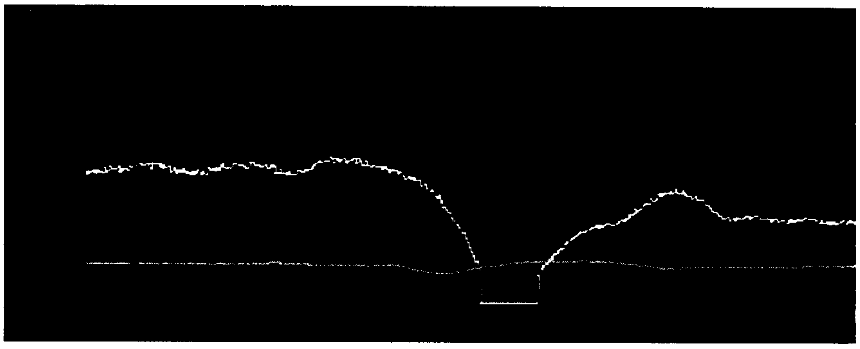


Figure18. Curves for increased gas and liquid volume in the closed loop

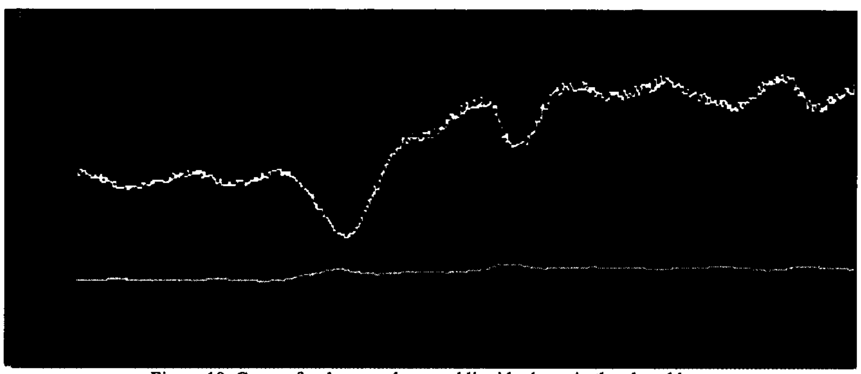


Figure 19. Curves for decreased gas and liquidvolume in the closed loop

5. EXPERIMENT ON OIL-GAS-WATER SEPARATION

After the liquid level is controlled stably, experiments on separation are done. In the experiments, the given oil-water liquid flux changes from 20 m^3/d to 150m^3/d, the water content rate in the oil-water mixture changes from 20% to 80%, the gas changes from 100 m^3/d to 550 m^3/d. Table 3 gives the test data. Test data shows that the maximum comparative errors between measured volume and practically provided liquid volume is 2.5%; the maximum comparative errors between measured volume and practically provided gas volume is -2.1%. The maximum flux burthen is 138.45 m^3/d of liquid flux and 540.62 m^3/d of gas flux. The minimum burthen flux is 21.32 m^3/d of liquid flux and 102.3 m^3/d of gas flux. Originally, the sizes of the main parts of the separator are designed according to gravity effect principle with maximum liquid flux burthen 50 m^3/d and gas flux 150 m^3/d . So the results of experiments show that the spiral tube compound separator is three times as efficient as the same size gravity separator in separation.

Table 3. Test data of gas-liquid separation

Test Times	Liquid measurement			Gas measurement		
	Standard value	Measured value	Error	Standard value	Measured value	Error
1	21.32	21.86	2.5%	102.61	104.43	1.9%
2	20.19	20.06	-0.6%	480.38	470.19	-2.1%
3	71.12	71.50	0.5%	200.84	198.39	-1.2%
4	77.05	76.18	-1.1%	303.7	304.56	0.3%
5	128.02	126.70	-1.0%	112.30	110.05	-2.0%
6	128.45	126.91	-1.2%	499.28	508.76	1.9%
7	138.45	140.32	1.4%	540.62	551.8	2.0%
8	151.10	153.51	1.6%	496.09	490.66	-1.1%

6. CONCLUSION

The structure of the spiral tube compound separator is an unique creation. The numerical simulation and test experiments prove that the structure design of the separator is good, and the compound effects of gravity and centrifugal force is better than single gravity effect. The separator has self stability in certain mixture burthen range. But when the burthen is out of the range it is necessary to control the separator's level automatically. The plan to keep liquid level stably through controlling flux of gas exit is feasible. The fuzzy PID controller keeps the separator in stable operation properly. The close loop system has good anti-jamming performance. And the test experiments show that the compound autocontrol separator is three times as efficient as the same size gravity separator in practical separation. Its advantages of ideal separating efficiency, small size and low cost will certainly bring it into wide applications in the future.

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