Design and System Development of a New On-line Recycled Water Clean-up Technology

Hui QUAN [*1], Rennian LI [2], Qingmiao SU [3], Tinghe Bai [4]

[1, 2, 4] School of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou, China

[3] School of Petrochemical Technology, Lanzhou University of Technology, Lanzhou, China

[*1] quanh2010@163.com; [2] lirn@lut.cn; [3] angelasu1985@163.com

***Abstract*- Based on the stir and separation, a new method is put forward to clean the deposit in sedimentation pool. Using the similarity theory in the design of experiment rig simulated a sedimentation tank clean-up system. The rationality of developing the industrial recycled water clean-up system was verified by theoretical analysis and numerical simulation (CFD) and the method to test "3D" research problems in the laboratory PIV flow field. In order to ensure the accuracy of the verification, the numerical simulation and PIV experimental model were designed at the ratio of 1:1. Results indicate that the mixture coefficient of muzzle is about 0.7； in different pressure conditions. The fluid boundary which spouted from combing tube can be regarded as a line and it has same angle with the combing tube. Experiment data also indicate that water speed is below 0.1 m/s on top of muzzle 1m zone. Axial velocity of fluid spouted from muzzle is measured and empirical formula is put forward. The best distance is 200mm between muzzles which determined by experiment, which ensures the level of clear water at the upper layer of the sedimentation tank, meeting the demand for industrial water.**

Keywords*- *Recycled Water; Clean Dirt; Clear Mud Spray Sweeping Machine; Sludge Absorption Tube; PIV

I. INTRODUCTION

The traditional water treatment plant settling tank bottom sludge removal using emptying the settling tank water later, Utilizing mechanical plant equipment or artificial dredged bottom sludge. This method need to interrupt the operation of sedimentation tanks, and higher cost [1-5]. This paper presents a new clean-up technology for the sedimentation tank, the basic idea of which is to deploy jet nozzles at the bottom of the tank to stir the sludge there and then the sludge with high concentration can be pumped out by the slugger before sent into the filter tank to separate water from it. This system enables continuous production and reduces clean-up costs.

At the current level of technology in China, two methods are mainly adopted by industrial enterprises to clean up suspended solids like sludge. The first method is to remove suspended solids in water by draining and changing the water in quantity, which, on the one hand, wastes a lot of water as the amount of water consumed is 10~15 times that of the sludge discharged according to statistics and on the other hand, discharges a large amount of those useful chemical elements used to purify the industrial water and stabilize its quality together with the sludge. In the long run, this clean-up effect of this method is not ideal and causes deposition of silt in the long-term operation, decreasing the effective space and the equipment's operating efficiency. The second method is to clean up the suspended solids like sludge manually or mechanically by switching or stopping the equipment and facilities, which actually requires more additional equipment and facilities and needs to stop all or part of the production system, impacting the continuous production and operation. Meanwhile, in this method, the great amount of sludge has to be cleaned in a short time, thus causing difficulties in transporting the sludge or affecting the normal operation and water treatment quality of the sewage treatment system when the sludge enters into it [1]. In contrast, development of the cycled water clean-up system makes it possible to clean up the sludge in the cycled water system without machine halts in industrial production, hence having great practical significance and application value in industrial water.

II. DESCRIPTION OF SYSTEM

A. Technical Requirements on On-Line Clean-Up System

In view of the nature of sludge in industrial recycled water system and the impact that the adhesiveness, sedimentation rate, density and mobility of the sludge have on the hydrodynamics of the sludge, some key devices such as the clear mud spray sweeping machine and the sludge absorption are designed to meet the following requirements in their hydrodynamic performance:

- To ensure that the hydrodynamics of the sludge clean-up system follow the principle of high clean-up efficiency.
- To ensure that this sludge clean-up system has no or little influence on the water quality produced by the recycled water system during its online operation .
- To ensure that the sludge in the industrial production operation system can be cleaned thoroughly while the industrial production system does not allow a lot of water to pass through the clean-up system to increase its load and reduce the efficiency of sludge cleaning.

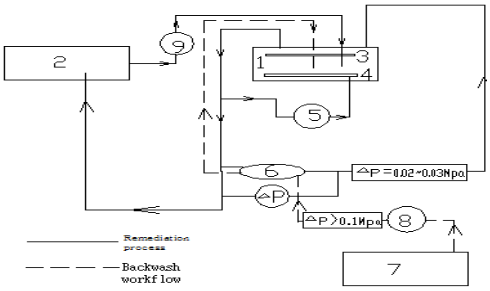
B. Process Drawing of the Recycled Water Clean-Up System

The nozzles and the absorption tube are the core of the clean-up system. The sludge at the bottom of the sedimentation tank should be adequately stirred so that it can be taken out by the absorption tube but should not be over stirred to influence the upper water. Therefore, precise control of parameters of the nozzles and the absorption tube is the key to efficient operation of the system.

The basic idea of which is to deploy jet nozzles at the bottom of the tank to stir the sludge there and stratify it through fluid motions so that the slugger with high concentration can be pumped out by the slugger before sent into the filter tank to separate water from it. This system enables continuous production and reduces clean-up costs. The process drawing as shown in Fig. 1 (a) and (b) as follows. Whether the separation phenomenon in the motion is laminar or turbulent is determined by whether the reynolds number exceeds the its critical number.

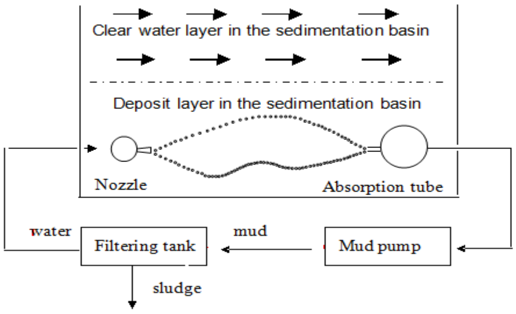
$$Re = VL/v \qquad (1)$$

Where V is the sectional average speed, ν is the viscosity coefficient and L is the distance from the object edge point.



1.cesspool A 2.cesspool B 3.sludge absorption tube
4.clear mud spray sweeping machine 5.cleaning pump
6. filter 7.pump 8.backwash pump 9.sludge pump

(a)



(b)

Fig. 1 Process drawing of the recycled water clean-up system

III. NUMERICAL CALCULATION AND RESULTS ANALYSIS

A. Basic Parameters

The experiment system consists of the water tank, the jet pipe, the absorption tube, fluid transportation and measurements system. Detailed parameters are listed in Table 1.

TABLE I BASIC PARAMETERS OF THE MODEL

Water tank			Jet pipe			Absorption tube		
L /mm	*W /mm*	*H /mm*	*Cali-ber /mm*	*Num-ber /n*	*Spa-cing /mm*	*Cali-ber /mm*	*Num-ber /n*	*Spacing /mm*
2585	2100	1500	159	12	200	159	24	100

The physical properties of the suspended solids in the recycled water are shown in Table 2, in which the numerical simulations are based on specific conditions within the scope of their values so as to reflect the actual situation more accurately.

TABLE II BASIC PARAMETERS FOR PHYSICAL PROPERTIES OF THE SUSPENDED SOLIDS

Grain diameter D/μm	Volume Concentra-tion Vof/mg/l	Density ρ /g/cm³	Ph value
85~95	20~40	0.95~1.0	7~9

The model was designed in the three-dimensional model software PRO/E and then imported to the GAMBIT for overall partition using the highly adaptable T-grid, generating more than 6.5 million computing grids. Meanwhile, To generate, and the grid independence was also checked.

B. Numerical Method

The velocity-inlet boundary conditions were adopted at the entrance [2-3]. While the natural outflow boundary conditions were used at the exit.

In the clean-up numerical simulation with the solid-liquid two-phase flow as the media, the dispersion turbulence model of the Euler turbulence model was chosen depending on the circumstances [4], where it is appropriate to calculate the governing equation by the standard k-ε model (the correlation coefficient (C_μ = 0.09 , C_1 = 1.44, C_2 = 1.92, σ_k = 1.0, σ_ε = 1.3) is appropriate [5]. In order to save computing time on the premise of accuracy, the first-order upwind scheme was adopted for the convection discrete and centered difference for the dissipation. The convergence precision was set at 10^{-5} and the iterative solution of the pressure-speed equation was performed by the SIMPLE algorithm.

C. Numerical Simulation Results and Analysis

The vertical of nozzle and horizontal velocity distributions of the recycled water tank resulted from the numerical simulation of Computational Fluid Dynamics (CFD) are indicated in Fig. 2.

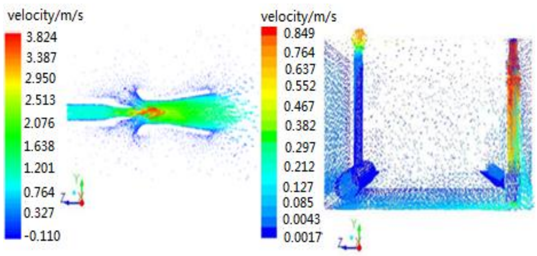


Fig. 2 Vertical and horizontal velocity distributions

Fig. 2 indicates that perpendicular to the bottom, stratified flow occurred in the sewage of the recycled water tank from the top to the bottom, the most upper layer being laminar while the medium and lower turbulent. This is because the fluid medium was simulated by taking the two-phase flow as the medium. The density of solid particles was greater than that of water, so the lower layer was generally a mixture of liquid precipitation, while the upper was clear water.

The vortex of the flow field produced by the jet purger was in the jet direction and the flow field peak occurred at the 2/3 of the distance between the outlet of the purger and the inlet of the absorption tube, which indicated that the jet purger of the sludge clean-up system had no effect on the peak, fully meeting the requirement that sludge clean-up system not affect the flow of the recycled water during its online operation.

IV. PIV EXPERIMENT SYSTEM

A. Experimental Facilities for PIV Velocity Measurement System

The experiment system consists of two parts: PIV (Particle Imaging Velocimetry) system and the experiment system. The former includes several subsystems such as the optical imaging system, image recording system and digital image analysis and display system [6].

Optical imaging system. (Main) uses two sets of YAG laser and a resolution of 2048 × 2048 pixel CCD, With the integration of inter-frame technology and fast transmission technology of data matrix, the collection area in the CCD-chip light source is about the thickness of 1.0mm, CCD acquisition area is about the size of 300mm × 300mm; The PIV system control and image analysis in this test is performed by the Insight 6.0 software whose working platform is Windows NT.

B. Structure of PIV Velocity Measurement System

In order to ensure the accuracy of verification, the dimensions of the simulated water tank were the same as those of the numerical simulation in the experiment system. The bottom and the two sides along the length of two sides and bottom were made of glass and were used for PIV velocity measurement [7-8]. The two sides along the Width direction were made of steel plates for easy the fixing and welding of water inlets and outlets. Similarly, the jet pipe and absorption tube adopted the parameters of numerical simulation [9-10]. The absorption holes and the nozzles were installed on the same horizontal plane and the pipe center line was 200mm from the bottom.

C. Choice of Tracer Particles

In actual conditions, the sludge is composed of particles of various sizes ranging from 80 ~ 100 μm in diameter according to industrial statistics analysis.

Analysis of the force on particles in the water shows that two forces are applied on the particles: the fluid force F_D (including friction and pressure drag) and the gravity mg.

The fluid force F_D is calculated by

$$F_D = \frac{1}{2} C_D \rho V^2 A \tag{2}$$

where F_D is the fluid force on the particles, A the frontal area of the particles, ρ the fluid density, C_D the drag coefficient and C_D is a function of Re, when the Reynolds number is greater than 103, C_D is considered to have nothing to do with Re. In this study, the Reynolds number is greater than 103 and V is the particle velocity.

The purpose of the experiment is to study the velocity distribution of deposit particles in the water, so the parameter of the experiment system is determined according to the dynamic similarity principle of the similarity theory to ensure that the force on the tracer particles in the experiment is the same as that in actual conditions.

Let the fluid resistance to deposit particles in the real fluid be $F_{D,}$ and the fluid resistance to tracer particles in the experiment fluid F_D,`. Then it can be deduced from formula (2) that:

$$\frac{r_s}{r_i} = \sqrt{\frac{\rho_{fi}}{\rho_{fs}}} \tag{3}$$

Where r_s and r_i are respectively the radius of the deposit particle and that of the tracer particle, ρ_{fs} and ρ_{ft} the actual fluid density and experiment fluid density.

Let the weight of the deposit particle be mg, and the weight of the tracer particle mg`. If mg equals mg`, then

$$\frac{r_s}{r_i} = \sqrt[3]{\frac{\rho_{pi}}{\rho_{ps}}} \tag{4}$$

Where ρ_{pi} and ρ_{ps} are respectively the density of the deposit particle and that of the tracer particle.

If Formulas (3) and (4) are correlated, then

$$\frac{\rho_{fi}}{\rho_{fs}} = \left(\frac{\rho_{pi}}{\rho_{ps}}\right)^{\frac{2}{3}} \tag{5}$$

Which indicates the relationship between the particle density and the fluid density. As it is difficult to ensure that the deposit density equals the density of the tracer particle in the experiment, the fluid density is adjusted to meet the requirements in (5). Table 3 and Fig. 3 are respectively the experimental facilities parameters and the experimental facilities.

Fig. 3 Experimenal facilities

TABLE III EXPERIMENAL FACILITIES

Name	Type
PIV particle	Diameter 80~100 μm Density 0.9~1g/cm^3, Type (Cenosphere/Microsphere)
Laser generator	Double resonance pulse Nd：YAG

PIV velocimeter	Kodak Megaplus ES1.0 and PIV 2000 processor
Flow meter	VSF XKLV 0~120m^3/h,PN1.6,DN150, LUBD precision: level 1.0
Pressure gauge	Precision: level 0.01 range:1.0MPa
Water pump	IS80-65-125,*Q*=15m^3/h,*H*=33m,*P*=30kw

D. PIV Test Experiment

1) The Flow Field Study of the Single Nozzle:

The role is to precipitate the nozzle bottom sediment stirred and mixed with the jet flow, and to understand the role of the strength of the nozzle and the jet velocity distribution in the water is the foundation of the injection system design.

Free submerged jet for under water problems have been studied by many scholars and has been relatively complete experimental and theoretical formulas. While the object of study in the literature are no free mixing tube submerged underwater jet, for the mixing tube nozzle (see Figure 4) is sparse. Thus, experiment first pair to the absorption tube does not work and only a spray nozzle when the flow field of sedimentation tanks were experimentally investigated.

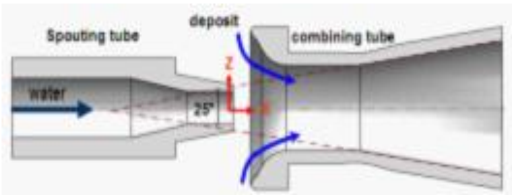


Fig. 4 The mixing tube nozzle

2) Structure of the Nozzle:

Nozzle consists of two parts, the front section is the jet tube and the back is mixing tube, which structure shown in Figure 4. It will stir the sediment around the injection port, making sediment and water mixture into the jet mixing tube when the injection tube water spray at high-speed .

3) Mixed Characteristic of the Nozzle:

The role of the nozzle is mixed with water and sediment, in order to quantitatively compare the pros and cons of blending property of nozzles, specially define the mixture coefficient φ as a measure of nature indicator of nozzles

$$\varphi = \frac{Q_{in}}{Q_{out}} \quad (5)$$

Where Qin is the jet flow at the entry hole of the nozzle, experimental numeric values of Qin is measured by the flow meter.

Qout is the total discharge out of the nozzle ,the sum of the jet flow and volume flow of the nozzle, which numeric values from the PIV measured velocity at the yet expansion calculated.

Adjust the jaw opening of the pump outlet governor valve, control the total inlet pressure (the nozzle inlet pressure) change from the 0.1 ~ 1 MPa, measure the outlet velocity of the nozzle, and convert it into the corresponding flow, obtained in Figure 5.

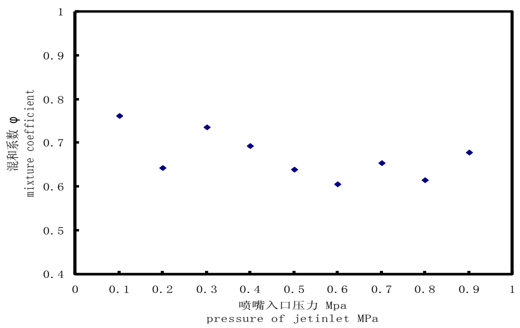


Fig. 5 Mixed characteristic of the nozzle

As can be seen from Fig. 5, with the nozzle pressure changes, the nozzle fluid mixture coefficient changed in a disorderly fashion from 0.6 ~ 0.8, this partly due to random changes in the testing process caused by the random error. Without considering the test's effect of errors, it can be approximated that the average mixture coefficient of nozzle maintained at about 0.7 under different pressure.

E. Jet Flow Field and Velocity Field under the Action of One Jet

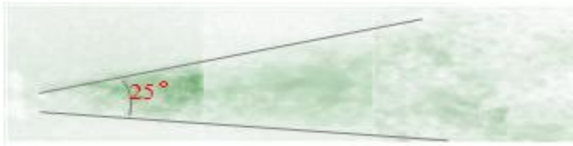


Fig. 6 Jet flow field and velocity field under the action of one jet

Fig. 6 indicates that the fluid spreads at the angle of 25° upon leaving the jet, which is the same as the angle of the combining tube of the jet. From the velocity field, it can be found that the longitudinal velocity of the fluid is far less than its axial velocity. These results are in accordance with research conclusions on underwater submerged jet. The jet boundary for underwater submerged jet is essentially a straight line.

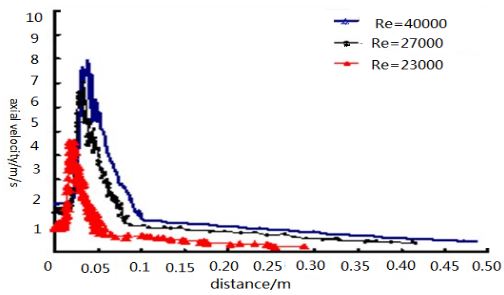


Fig. 7 Velocity change curve along the axis

Fig. 7 shows the axial velocity distribution of the jet at different Reynolds numbers. Take *Re* = 40000 for example, it can be seen from the figure that the velocity of the fluid sprayed from the jet moves from about 2 m/s to the maximum of about 8 m/s and begins to decline. The slowing-down process is divided into two stages, the rapid decline stage when the distance is 0.05 ~ 0.1m and the steady decline stage. When the distance is 0.5m, the axial velocity of the fluid is about 0.3 m/s. When *Re* = 12000 and the distance is 0.25m, the axial velocity of the fluid is about 0.1 m/s.

Analogizing the data on the three curves when the distance is 0.1 ~ 0.5m to the axial velocity formula of underwater submerged jet, we can get the regression formula as follows:

$$\frac{u_m}{u_0} = 3.1\sqrt{\frac{2b_0}{x}} \tag{6}$$

Where u_m is the axial velocity and u_0 the escape velocity at the jet.

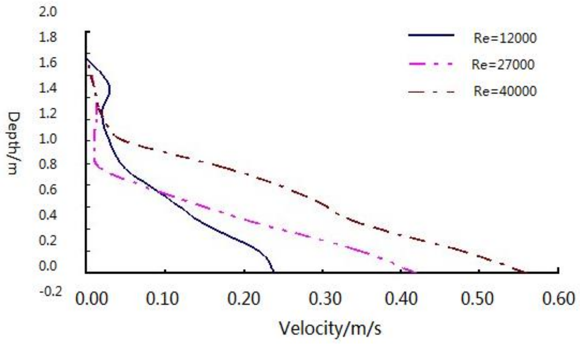


Fig. 8 Jet velocity distribution in the depth direction

Figure 8 shows the velocity distribution along the depth direction Z at different Re numbers when X = 0.6m. The figure indicates that:

1) The greater the distance from the jet, the faster the flow velocity drops. When Re=12,000, the axial velocity of the jet (Z = 0) is 0.55m/s, and when the distance from the jet center is 1.0 m (Z = 1.0m), the water velocity is reduced to 0.09 m/s.

2) Under the influence of the bottom walls of the tank, the water flow is no longer axisymmetric.

3) When the water depth is more than 1.0 m, the flow velocity is less than 0.1m.

F. Synergistic Effect of Multi-Nozzle Flow Field

Compared with the flow field generated by a single nozzle, flow field will change when the role of multi-nozzle joint.Reason for the change of flow field on the one hand from the interaction between the nozzle and nozzle interaction. The other hand, the mutual influence which generated from absorption tube and nozzle .

Further analyse the factors which affect the flow field of sedimentation tanks, the following aspects: (1) nozzle inlet velocity; (2) the spacing interval between the nozzle and the nozzle; (3) the distance between the nozzle and the absorption mouth; (4) the spacing interval between the absorption mouths; (5) flow rate out of the absorption mouth.

In this experiment, the relative position of jets and absorption ports is adjusted by changing the numbers of jets and absorption ports and their relative positions. The experiment has measured the flow field between one jet air purger and two absorption ports, the flow field between three jet purgers and six absorption ports and the flow field between twelve jet purgers and twenty-four absorption ports to determine the optimal interval between the jets.

The PIV test results indicate that the distributions of the above three flow fields are quite similar to each other. Fig. 7 shows the distribution of flow field with twelve jet purgers and twenty-four absorption ports.

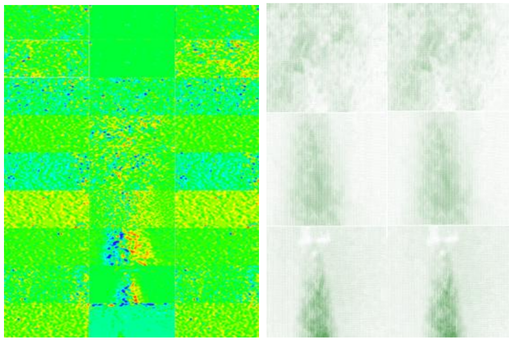


Fig. 9 Horizontally distributed velocity cloud and velocity distribution diagram

Fig. 9 is respectively the vorticity cloud and velocity vector diagram on the horizontal plane of the jet when the jet flow velocity is controlled at 2.2 m/s and the flow velocity at the absorption inlet at 1.3 m/s.

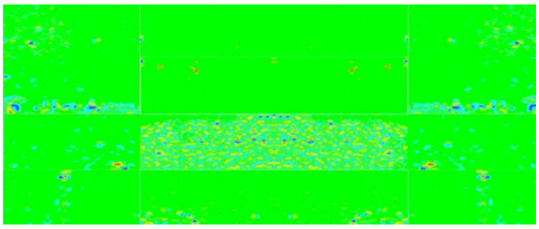


Fig. 10 Vertcal vorticity cloud

It can be drawn from Fig. 2 for numerical simulation and Figs. 9 and 10 for PIV flow field measurement that in the whole operation process of the system, the flow field produced by the jet purger is in the jet direction and the flow field peak occurred at the 2/3 of the distance between the outlet of the purger and the inlet of the absorption tube. The field flow produced by the jet purger is the same as that in CFD simulation, which further indicates that there is no field flow interference between the individual purgers of the sludge clean-up system. In addition, there are height restrictions on the influence that the jet purgers of the clean-up system have on the whole system operation process in the vertical plane, and combining the two pictures, we can see that the flow field vortexes produced by all the jet purgers are closely connected, which means that there is no gap between the jet purgers on the horizontal plane in the system operation; which hence fully meeting the requirement that sludge clean-up system not affect the flow of the recycled water during its online operation.

V. EXAMPLE

The industrial test was carried out in the recycled water system in an oil refining chemical industry from July to August in 2011. The flow oil separation tank in the company was one of the flow sedimentation tanks. Its main function was to separate oil. As water stayed there for a short time and the precipitation was not very prominent, so the tank was required to be cleaned annually. Each oil separation tank discharged 60 tons of sludge every year. In this experiment, it was reasonable to change the percentage of the system discharge capacity to the total filtration into the ratio of water inflow to the filtration capacity in the oil separation tank. The current water inflow of the oil separation tank is 450 m^3/h, the filtration capacity of the test equipment is 80 m^3/h, the turbidities for water inflow and outflow are respectively 90 mg/l, and 60mg/l, sludge removal rate is around 25% and the turbidity of the sludge sewage tank has been reduced to 7mg/l from 88mg/l. Therefore, the industrial test of the sludge clean-up system has achieved the ideal result. Fig. 11 is the record of the sludge removal rate and turbidity in the sludge discharge experiment of the oil separation tank.

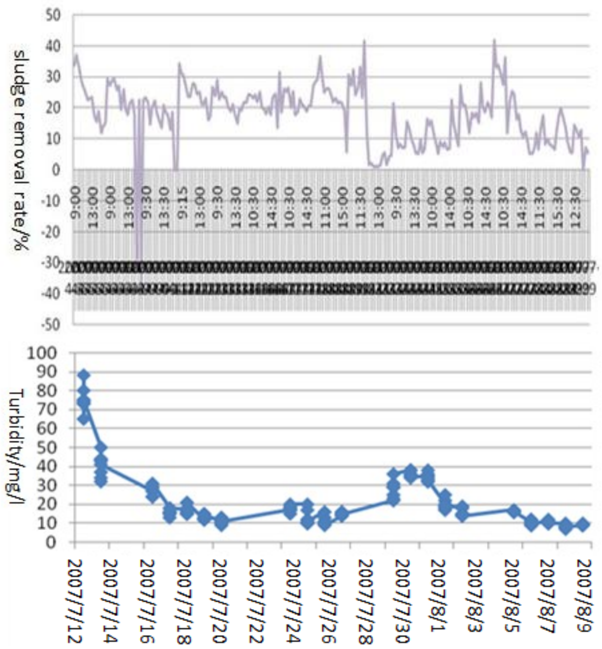


Fig.11 Sludge removal rate and turbidity in the sludge discharge experiment of the oil separation tank

VI. CONCLUSION

This system is able to achieve online clean-up, so the sludge clean-up of the recycled water system can be done without stopping the industrial production run. When the number of sludge absorption tubes is twice the number of the sludge spray sweepers with the spacing between the nozzles of 200mm, the nozzles' stir is the most ideal. The nozzles stir and stratify the fluid in the sedimentation tank and then pass the sludge through to filter to get cleaned. At this time, the vortex of the flow field produced by the jet purger is in the jet direction and the flow field occurs at the 2/3 of the distance between the outlet of the purger and the inlet of the absorption tube, which ensures the level of clear water at the upper layer of the sedimentation tank, meeting the demand for industrial water.

VII. ACKNOWLEDGMENTS

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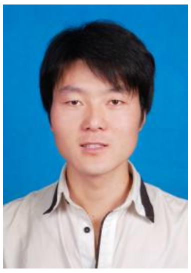

Hui QUAN, PhD. Candidate, School of Energy and Power Engineering, Lanzhou University of technology, Lanzhou, China. He obtained his B.Sc. degree in 2012 from Lanzhou University of technology. His major research interests include Hydro-mechanical solid-liquid two-phase flow theory and Application.

E-mail: quanh2010@163.com

Rennian LI, Supervisor of PhD Candidates, currently is an associate professor of school of Energy and Power Engineering, Lanzhou University of technology, Lanzhou, China. His major research interests include hydro-mechanical solid-liquid two-phase flow theory, multiphase flow and wind turbine.

E-mail: lirn@lut.cn

Qingmiao SU, Postgraduate of Master, School of Petrochemical Technology, Lanzhou University of technology, Lanzhou 730050, China. Her major research interests include the safety of valve and fluid static seal.

E-mail: angelasu1985@163.com