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Early Warning on Mass Imbalance and Clean-in-Place Strategy for Rotor of Rotating Packed Bed

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ABSTRACT Rotating packed bed is a new high-gravity gas-liquid mass-transfer equipment. The gas-liquid phase chemically reacts to the wire mesh packing of the rotor, and solid products easily adhere to the wire mesh packing, resulting in rotor vibration caused by rotor mass imbalance, thereby causing damage to bearings and seals. Such a fact hinders the long-cycle operation and large-scale process of the rotating packed bed. Research institutions and scholars all around the world have done a lot of work on mechanical balance. But the current mechanical balance is only temporary balance, and it does not fundamentally solve the problem of vibration and mass transfer efficiency degradation caused by the mass imbalance of the reaction product adhering to the rotating packed bed rotor. According to this situation, the strategy of early warning on mass imbalance and clean-in-place for rotating packed bed rotor is proposed. Firstly, the relationship of pressure, flow rate, and the void ratio of packing is established by numerical simulation. And the change of the rotor void ratio in the rotating packed bed can be calculated from the flow velocity or pressure change. Secondly, a dual-electromagnetic rotating packing bed based on ultrasonic cleaning is designed. Once the adhesion exceeds the threshold of early warning, the electromagnetic clutch controls the current rotating packed bed to stop working and the spare rotating packed bed to start to work. Two rotating packed bed structures complement each other to reduce the rate of the shutdown and avoid damage to bearings and seals.

INDEX TERMS Numerical simulation, rotating packed bed, rotor imbalance, unbalanced quantity reduction.

I. INTRODUCTION

Rotating Packed Bed (RPB) is widely used in separation, absorption, and reaction [1]. Compared with traditional reaction vessels, its advantages include: first, a centrifugal force field is generated by the high-speed rotation of the internal rotor, so that the flow of the fluid inside can be accelerated, thus achieving micro-mixing and enhancement of mass transfer [2]. Second, the gas-liquid mass transfer is mainly carried out in the rotating rotor and packing. During rotation, the wire mesh packing continuously cut the liquid, thus effectively increasing the area of gas-liquid mass transfer [3].

The solid particles in the reaction liquid or intermediate solid products produced during mass transfer easily adhere to the wire mesh packing of the rotor. Such fact not only reduces the volume of the rotor reaction mass transfer space but also makes the rotor mass distribution uneven, resulting in rotor vibration caused by rotor mass imbalance [4], [5], thereby causing damage to bearings and seals [6]. When there is adhesion on the packing, in-place active balancing does not solve the problem of reducing the volume of the actual mass transfer space, but can only achieve temporary balance. Therefore, with the existing techniques, shutting down, disassembling, and cleaning the rotor is the only feasible way for resuming normal operation. Seals and bearings that are worn due to uneven rotor mass distribution can only be replaced.

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Many research institutions and scholars at home and abroad have done a considerable amount of work on rotor balance [7], [8]. And they have made significant progress in fault detection and rotor balancing [9]–[11]. Although the current mechanical balancing method for rotors [12] can temporarily resolve mass unevenness, in the chemical industry, the on-going adhesion will still cause imbalance, which leads to reducing mass transfer efficiency. To ensure the long-term operation of the equipment and avoid economic losses caused by shutting down, it is necessary to design a rotating packed bed structure that can keep running for a long period without the need of cleaning by shutdown to reduce the rate of shutdowns as much as possible and enable the equipment to run stably for a long period, thereby improving the production efficiency of the equipment.

For the reasonable timing of cleaning, early warning on excessive adhesion is necessary. Through experiments [13], it was found that due to the adhesive byproduct continuously produced on rotor packing, mass transfer space shrinks, flow velocity of gas decreases, and the pressure drop in the rotating packed bed continuous to increase. Therefore, in this study, a hydrodynamic model of rotating packed bed is established, and the relationship of pressure, flow rate, the void ratio of packing is established by numerical simulation to achieve in-place early warning of rotor mass imbalance. This method is different from the traditional method. The traditional vibration signal monitoring and extraction method studies the rotor imbalance from the perspective of mechanical vibration, while the method proposed in this paper integrates the laws of chemical reaction engineering into rotor dynamics and mechanical design. The research not only studies the effect of chemical reaction parameter variables on the adhesion of substances to fillers and the distribution of substances in fillers, but also establishes the rotor dynamics model considering the process of chemical mass transfer to explore the effect of mass imbalance. With the method, this paper proposes the strategy of early warning on mass imbalance and clean-in-place for the rotating packed bed rotor. The strategy implements in-place monitoring of rotor adhesion status. Once the adhesion exceeds the threshold of early warning, the electromagnetic clutch controls the current rotating packed bed to stop working, and the spare rotating packed bed starts to work. Two rotating packed bed structures complement each other to reduce the rate of the shutdown and avoid damage to bearings and seals.

II. NUMERICAL SIMULATION AND CONSTRUCTION OF EARLY WARNING MODEL

To study the relationship between rotor mass imbalance and fluid flow state [14]–[16], in this paper, a CFD numerical simulation is used, and the parameter sensitivity experiment is set with the void ratio of packing as a single factor variable to obtain the coupling relationship of pressure, flow rate, and the void ratio, thus establishing the method for early warning of rotor status based on reaction parameters.

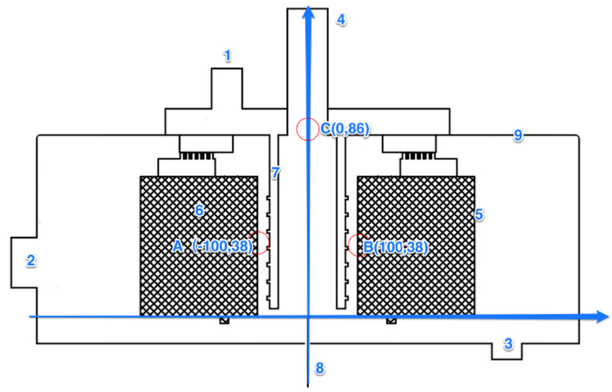

FIGURE 1. Structure of rotating packed bed.

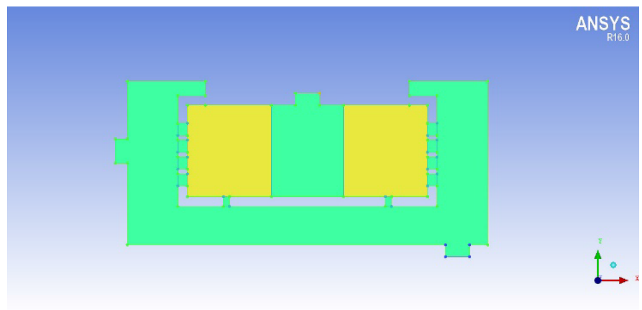

FIGURE 2. The fluid partition structure of the RPB reaction model.

A. PHYSICAL MODEL

The main structure of the rotating packed bed includes gas and liquid inlets and outlets, rotor, packing, spray pipe, rotating shaft, and housing. When the rotating packed bed runs, the raw material liquid enters the spray pipe from the liquid inlet and is sprayed on the rotor packing; the raw material gas enters the rotor packing from the gas inlet and reacts with the raw material liquid; after the reaction, the reaction gas flows out from the gas outlet, and the reaction liquid flows out from the liquid outlet. The constructed physical model is shown in Figure 1. The meaning of the labels in Figure 1 are as follows: 1. Liquid inlet 2. Gas inlet 3. Liquid outlet 4. Gas outlet 5. Rotor 6. Filler 7. Spray pipe 8. Rotating shaft 9. Housing

When the equipment runs, the raw material liquid and the raw material gas react mainly in packing and produce adhesions on packing. Initially, the packing is a wire mesh structure, and the void ratio of packing decreases with the adhesion of byproduct. The process can be simulated using a porous media model. Therefore, when dividing the fluid flow structure, the packing part is distinguished from other fluid parts. For the rotating packed bed designed in this paper, the divided fluid structure is shown in Figure 2. The green part is the area where the fluid flows, and the yellow part is the area where the fluid flows through the porous medium.

TABLE 1. Physical model parameters of rotating packed bed.

Variables	Values
Inner diameter of packing (mm)	60
Outer diameter of packing (mm)	200
Inner diameter of rotating packed bed (mm)	300
Height of rotating packed bed (mm)	136
Feed gas flow (m^3/h)	20
Packing material density (kg/m^3)	7293
Gas inlet and outlet pipe diameter (mm)	20
Liquid inlet and outlet pipe diameter (mm)	20
Height of packing (mm)	76
Rotor opening aperture (mm)	10
Flow rate of raw material liquid (L/h)	800
Void ratio (%)	97

TABLE 2. Position and motion of jet source.

No.	X(mm)	Y(mm)	X-velocity(m/s)
1	30	71	1.41
2	-30	71	-1.41
3	30	66	1.41
4	-30	66	-1.41
5	30	61	1.41
6	-30	61	-1.41
7	30	56	1.41
8	-30	56	-1.41
9	30	51	1.41
10	-30	51	-1.41
11	30	46	1.41
12	-30	46	-1.41
13	30	41	1.41
14	-30	41	-1.41
15	30	36	1.41
16	-30	36	-1.41
17	30	31	1.41
18	-30	31	-1.41
19	30	26	1.41
20	-30	26	-1.41
21	30	21	1.41
22	-30	21	-1.41
23	30	16	1.41
24	-30	16	-1.41
25	30	11	1.41
26	-30	11	-1.41
27	30	6	1.41
28	-30	6	-1.41

Table 1 shows the parameters of the equipment structure, the physical properties parameters, and reaction state parameters of wire mesh packing.

B. SIMULATION EXPERIMENTS OF FLOW VELOCITY, PRESSURE CHANGE AND DISCRETE PHASE PARTICLE MOTION

In the simulation, the position of the spray source is the position of the opening in the spray pipe; the flow rate of the spray source, i.e., the flow rate of the raw material liquid through the spray pipe is 0.2 kg/s; the diameter of the spray source, i.e., the diameter of the spray pipe is 2mm; the data are shown in Table 2.

The mass transfer of a rotating packed bed is an unsteady state process in which the distribution, pressure, and flow rate of components constantly change over time. When the iterative residuals of the monitored values of pressure, flow rate, energy, and composition reach equilibrium, the reaction is considered to have reached equilibrium. Taking the steady-state of gas flow and liquid flow of raw material as the initial field, after adding the energy model, turbulence model, porous media model, discrete phase ejection model and frame motion model [17], iterative solution was performed to simulate pressure changes, discrete phase particle motion, and speed changes during the reaction.

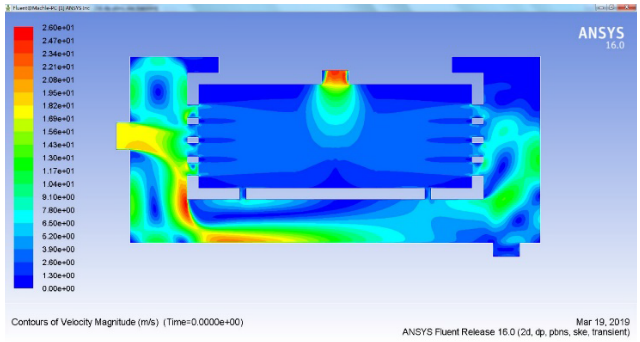

FIGURE 3. Gas velocity amplitude isoline at 0.97 voids.

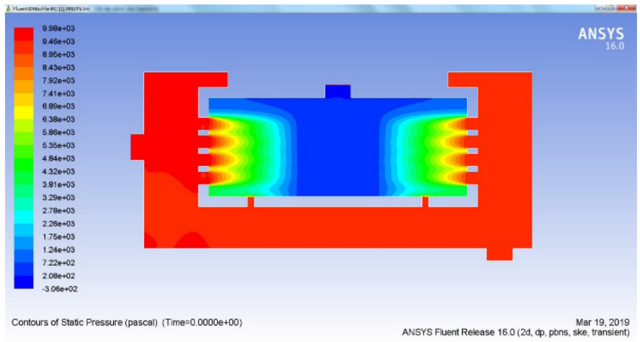

FIGURE 4. Static pressure contour map at 0.97 voids.

In this paper, the plane of symmetry of the gas inlet tube is selected as the plane for research. At this point, the void ratio of porous media is 0.97, as the adhesion on the rotor is not taken into consideration. Figure 3 is a contour map of the amplitude of the gas phase velocity in the steady state. Figure 4 is a contour map of the static pressure in a steady state. Figure 5 is a contour map of liquid particle concentration in a steady state.

Result analysis: For the simulated operating conditions, when the reaction reaches equilibrium, (1) the gas phase velocity reaches its maximum at the gas phase outlet, the gas phase velocity in packing is small, and vortices may be generated in the outer cavity of the rotating packed bed near the gas phase inlet; (2) the pressure in the gas inlet and the outer cavity is basically unchanged, which is the maximum pressure; after the gas phase enters the rotor packing, the pressure decreases continuously, reaching a minimum value in the inner cavity of the rotor, which is consistent with the pressure at the gas outlet; (3) the liquid particle concentration contour

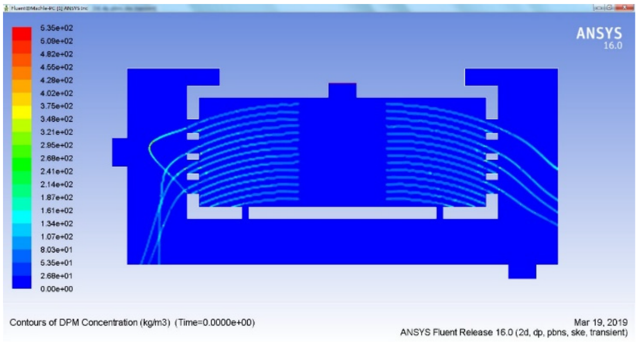

FIGURE 5. Contour map of liquid particle concentration at 0.97 voids.

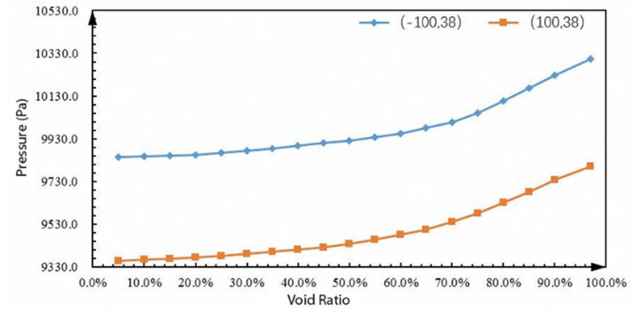

FIGURE 6. Effect of void ratio change on pressure at (-100,38) and (100,38) coordinate points.

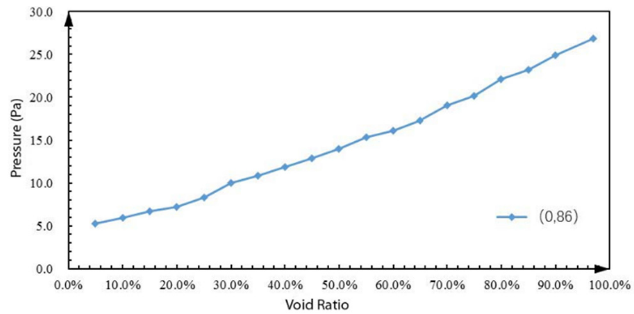

FIGURE 7. The influence of void ratio change on the pressure at the coordinate point (0,86).

map mainly shows the flow direction of the liquid phase, but the concentration has hardly changed.

The above analysis shows (1) when the reaction reaches equilibrium in a rotating packed bed, pressure, and gas velocity are volatile state parameters, which is of research significance; (2) there is almost no change in the liquid concentration, which is temporary of no significance in the study of this article. For the pressure, the pressure at the gas inlet and outlet can be studied; for the velocity, the gas flow velocity at the gas inlet and outlet can be studied.

C. ESTABLISHMENT OF EARLY WARNING MODEL OF FLOW VELOCITY AND PRESSURE

In this paper, to study the effect of mass of rotor adhesion on the state of fluid flow, with void ratio as a single factor variable, experiments were conducted when the void ratio was set to 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, and 97% respectively to study the effect of void ratio changes on pressure and gas velocity at different locations. The void ratio of packing was inversely proportional to the mass of adhesion on the rotor, so the change in mass of adhesion could be derived from the change in porosity. For the representation of experiment results, three positions were selected, including the midpoint of the inner wall of the left end rotor (−100, 38), the midpoint of the inner wall of the right end rotor (100, 38), and the midpoint of the reaction gas outlet (0, 86).

1) SIMULATION OF PARAMETER SENSITIVITY OF PRESSURE TO MASS OF ROTOR ADHESION AND ESTABLISHMENT OF COUPLING FORMULA

The effect of the rotating packed bed rotor void ratio on the pressures on the above-mentioned positions is shown in Figure 6 and Figure 7.

Figure 6 and Figure 7 show that as the void ratio increased, the pressure at the inner wall of the rotor and the reaction gas outlet gradually increased, and the rate of pressure change at the inner wall of the rotor gradually increased; when the void ratio reached 97%, the maximum pressure was obtained through simulation.

After the obtained data was fitted by the formula, the relationship between pressure and the void ratio was derived as follows:

(1) The relationship between pressure and the void ratio at (−100, 38):

$$P = 9841.52 - 46.23x + 2540.38x^2 - 21392.82x^3 \quad (1)$$

(2) The relationship between pressure and the void ratio at (100, 38):

$$P = 9339.55 + 606.18x - 5619.77x^2 + 22543.08x^3 \quad (2)$$

(3) The relationship between pressure and the void ratio at (0, 86):

$$P = 2.81 + 76.46x - 700.03x^2 + 2740.72x^3 \quad (3)$$

In the formula, P is the pressure at each coordinate point, in Pa; x is the void ratio of the rotor packing;

2) SIMULATION OF PARAMETER SENSITIVITY OF VELOCITY TO MASS OF ROTOR ADHESION AND ESTABLISHMENT OF COUPLING FORMULA

The effect of the change in rotating packed bed rotor void ratio on the gas phase velocity at the above positions is shown in Figures 8, 9, and 10.

Figure 8 shows that as the void ratio increased, the gas phase velocity on the left inner wall of the rotor fluctuated greatly and displayed large randomness. Therefore, in the

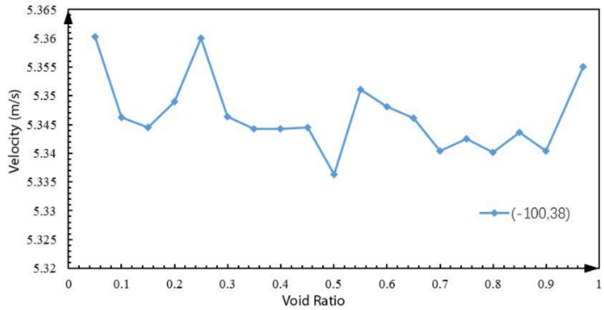

FIGURE 8. The influence of void ratio change on the meteorological velocity at (−100,38).

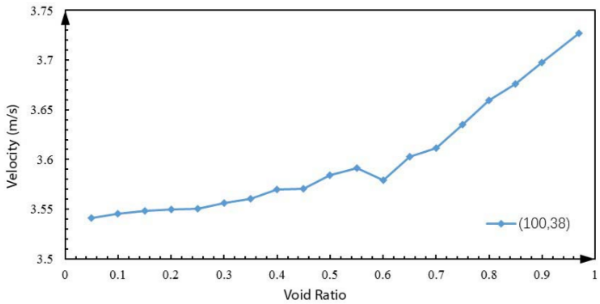

FIGURE 9. The influence of void ratio change on the meteorological velocity at (100,38).

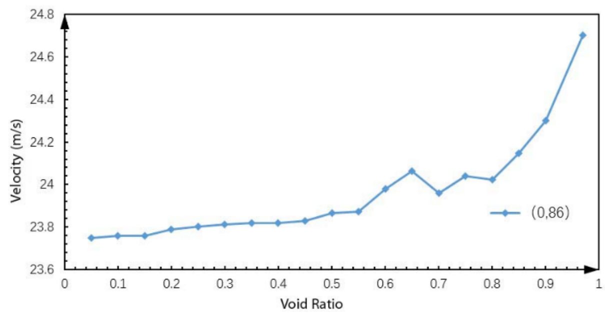

FIGURE 10. The influence of void ratio change on the meteorological velocity at (0,86).

study, the relationship between speed and void ratio for (−100, 38) with large fluctuations was not studied.

Figures 9 and 10 show that, as the void ratio increased, the speed at the right inner wall of the rotor and the reaction gas outlet gradually increased; when the void ratio reached 97%, the maximum gas phase velocity was obtained at the positions (100, 38) and (0, 86).

(1) The relationship between speed and the void ratio at (100, 38):

$$v = 3.54 + 0.08x \tag{4}$$

(2) The relationship between velocity and the void ratio at (0, 86):

$$v = 23.75 + 0.40x + 17.23x^2 - 222.89x^3 \tag{5}$$

In the formula, v is the velocity at each coordinate point, in m/s; x is the void ratio of the rotor packing;

3) RESEARCH METHOD OF EARLY WARNING ROTOR RUNNING STATE BASED ON REACTION PARAMETERS

In the study above, the coupling relationship between pressure, flow rate, and void ratio was established. The void ratio of the rotating packed bed rotor could be deduced by pressure and speed. It can be seen from Fig. 6 that when the void ratio is low, the effect of the void ratio changing on the pressure at the coordinate points (−100,38) and (100,38) is not obvious. As can be seen from Fig. 8, as the void ratio increases, the gas phase velocity fluctuations on the left inner wall of the rotor fluctuate greatly and have large randomness. It can be seen from Fig. 9 that when the void ratio is around 0.6, the gas phase velocity fluctuation at point (100, 38) is relatively large, which will disturb the early warning effect. It can be seen from Fig. 10 that when the void ratio is 0.6-0.8, the gas phase velocity fluctuation is also large, and it will also interfere with the early warning effect. The curve in Fig.7 has small fluctuations, and the gas outlet pressure varies significantly with the void ratio, so the gas outlet pressure is selected as the monitoring object. In this section, the research method of rotor warning based on reaction parameters is thus presented. By monitoring and calculating the void ratio, the timing of the clean-in-place of the rotor can be determined.

When the rotating packed bed is running, the pressure of the reaction gas outlet can be monitored. Through the coupling model of pressure and void ratio established in the previous article, the current rotor void ratio was obtained through analysis. Rotor void ratio is inversely proportional to the mass of rotor adhesion. Therefore, the change in mass of rotor adhesion can be obtained through the change in rotor void ratio and can be used as a reference for early warning of the rotating packed bed. The scheme for determining the warning threshold includes the following four steps. (1) Selecting different void ratio specifications to conduct CFD simulation. (2) Modifying the coupling relationship between pressure and void ratio obtained in the numerical simulation. (3) Obtaining the critical value of the void ratio of the rotor packing during the normal operation of the rotating packed bed based on expert experience. (4) Calculating the pressure value at this time from the correction relationship between pressure and void ratio. This pressure value should be the early warning threshold. By referring to the early warning threshold value, the appropriate timing for cleaning the rotor of the rotating packed bed can be determined, thus improving efficiency and avoiding potential safety hazards in practice.

III. STRUCTURE AND STRATEGY OF CLEAN-IN-PLACE OF THE ROTOR

A. THE STRUCTURE DESIGN OF CLEAN-IN-PLACE OF ROTOR

In this section, after the early warning method of rotor unbalance fault based on the response parameters is proposed,

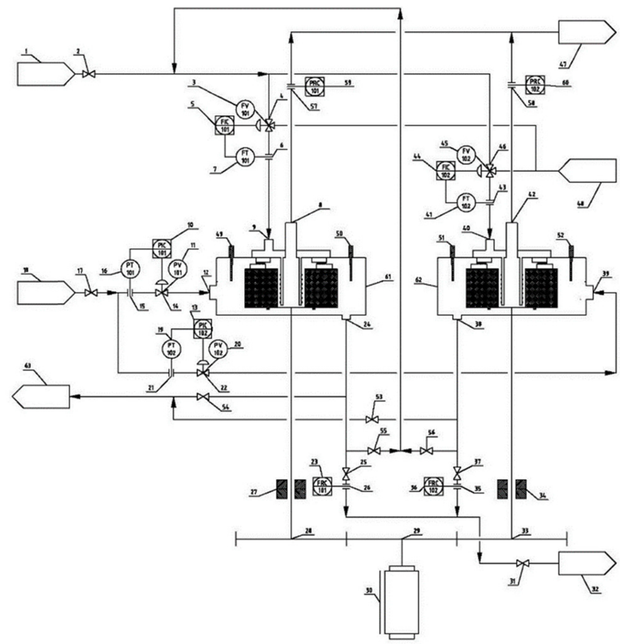

FIGURE 11. Schematic diagram of double electromagnetic clutch RPB based on ultrasonic cleaning.

in order to implement in-place replacement and cleaning of the rotor, a dual electromagnetic clutch rotating packed bed structure based on ultrasonic cleaning is designed, as shown in Figure 11. This structure has two features:

(1) A mechanical structure of the gearbox and the electromagnetic clutch was designed. A gearbox is installed on the upper end of the motor output shaft, and three gears of the same size and meshing with each other are installed in the gearbox. The gear in the middle is connected to the motor output shaft, and the gears at both ends are connected to the rotating shafts of two rotating packed beds, respectively. The rotating shaft consists of two parts, the meshing part with the gearbox, i.e., the driving part and the connecting part with the rotating packed bed, i.e., the driven part. An electromagnetic clutch is installed between the two parts to implementing the connection and disconnection from the driven part without stopping the rotation of the driving part.

(2) An ultrasonic cleaning structure that complements the rotating packed bed was designed. The ultrasonic probe is fixed on the top of the rotating packed bed housing through screws. To enhance ultrasonic cavitation, two symmetrically-placed ultrasonic probes are installed in each rotating packed bed. When cleaning is needed, it can be turned on by an external ultrasonic generator.

The labels in the figure: 1. Raw material liquid inlet, 2. Valve, 3. Flow regulating instrument, 4. Regulating valve, 5. Flow controller, 6. Flow meter, 7. Flow transmitter, 8. Gas outlet, 9. Liquid inlet, 10 Pressure controller, 11. Pressure-regulating instrument, 12. Gas inlet, 13. Pressure controller, 14. Regulating valve, 15. Pressure gauge, 16. Pressure transmitter, 17. Valve, 18. Raw gas inlet, 19. Pressure transmitter, 20. Pressure regulation instrument, 21. Pressure gauge, 22. Regulator valve, 23. Flow measurement instrument, 24. Liquid outlet, 25. Valve, 26. Flow meter, 27. Electromagnetic clutch, 28-29. Gear, 30. Motor, 31. Valve, 32. Liquid product outlet, 33. Gear, 34. Electromagnetic clutch, 35. Flow meter, 36. Flow measurement instrument, 37. Valve, 38. Liquid outlet, 39. Gas inlet, 40. Liquid inlet, 41. Flow transmitter, 42. Gas outlet, 43. Flow meter, 44. Flow controller, 45. Flow regulating instrument, 46. Regulating valve, 47. Gas product outlet, 48. Cleansing water inlet, 49-52. Ultrasonic probe, 53-56. Valve, 57-58. Pressure gauge, 59. Pressure measuring instrument, 60. Pressure measuring instrument, 61-62. Rotating packed bed, 63. Cleansing water outlet.

B. THE STRUCTURE DESIGN OF CLEAN-IN-PLACE OF THE ROTOR

The rotor clean-in-place control strategy of a dual electromagnetic clutch rotating packed bed based on ultrasonic cleaning consists of three steps. First, by detecting the pressure of the gas outlet pipeline part and referring to the coupling formula (3) of pressure and void ratio, determine the state of mass of rotor adhesion and the timing of cleaning the rotor packing; second, through the process control system and the electromagnetic clutch equipment, replace the rotating packed bed in operation to be cleaned with the spare rotating packed bed, and guarantee continuity of operation; finally, through the process control system and the ultrasonic cleaning equipment, clean the rotating packed bed through ultrasonic cavitation and put it into standby status. Below are detailed instructions for the three steps.

Step 1: Monitor the status of mass of rotor adhesion

1) During the initial stage of reaction, the raw material liquid flows into the rotating packed bed through the valve, regulating valve, and flow meter that is installed and opened on the raw material liquid inlet pipeline; the raw gas flows into the rotating packed bed through the opened valve, pressure gauge, and regulating valve; the produced gas flows through the gas outlet, pressure gauge and pressure measuring instrument to the gas outlet; the produced liquid flows through the valve, flow meter, and valve opened on the liquid outlet pipeline to the liquid outlet.

2) When the void ratio calculated by the pressure-void ratio coupling formula (3) from the pressure detection value on the gas outlet line is lower than the early warning threshold, the mass of the adhesion on the rotor exceeds a critical value, and the rotor needs to be cleaned at this point.

Step 2: Control strategy and replacement of rotating packed bed with electromagnetic clutch equipment

1) Next, complete the in-place replacement of the rotating packed bed that needs to be cleaned; first, close the spare electromagnetic clutch to start the spare rotating packed bed;

2) Open the regulating valve at the standby raw material liquid inlet through the flow controller, so that the raw material liquid flows into the standby rotating packed bed;

3) Open the valve at the return pipeline (56 or 55, subject to actual circumstance), so that the raw material liquid that has

just flowed into the standby rotating packed bed flows into the raw material liquid inlet line through the return pipeline;

4) After a certain period of time, open the regulating valve at the standby raw material gas inlet through the pressure controller to allow the raw material gas to flow into the standby rotating packed bed; open the valve of the standby production liquid line to make the production liquid flow to the liquid outlet; close the valve of the return pipeline so that the raw material liquid no longer flows back;

5) Close the regulating valve at the inlet of the raw gas of the rotating packed bed to be cleaned through the pressure controller so that the generated gas no longer flows into it; after a period of time, close the regulating valve at the raw material liquid inlet of the rotating packed bed to be cleaned by the flow controller, so that the raw material liquid no longer flows into it;

6) When the flow measuring instrument of the rotating packed bed to be cleaned detects that the flow is 0, the reaction finally stops; at this point, cut off its electromagnetic clutch, completely stop the rotating packed bed to be cleaned, and complete the in-place replacement of the rotating packed bed.

Step 3: Control strategy and rotor packing cleaning with ultrasonic cleaning equipment

1) First, close the valve at the outlet of the rotating packed bed to be cleaned to prevent the cleansing water from flowing out of the rotating packed bed;

2) Connect the valve of the washing water inlet to the valve in the direction of the rotating liquid packed inlet through the flow controller, so that the washing water flows into the rotating packed bed;

3) After an appropriate amount of cleansing water is injected, close the regulating valve at the inlet of the raw material liquid by the flow controller so that the washing water does not enter again;

4) Turn on the ultrasonic probe through an external ultrasonic generator for ultrasonic cleaning;

5) After the washing is done, open the valve at the washing water outlet pipeline to allow the washing water to flow into the washing water outlet and discharge the washing water;

At this point, the in-place cleaning of the rotating packed bed with ultrasonic cleaning by the dual electromagnetic clutch is finished.

IV. CONCLUSION

(1) In this paper, a rotating packed bed physical model is constructed and the numerical simulation is performed; simulation study of parameter sensitivity with packing porosity as a single factor variable is conducted; the coupling relationship between the sensitive parameters and the mass of rotor adhesion is established; based on this formula, an early warning model on rotor's operation status based on the reaction parameters is constructed.

(2) In this paper, a dual-electromagnetic rotating packing bed based on ultrasonic cleaning is designed for long-term operation; the connection and disconnection of the rotating shaft of the rotating packed bed is implemented by a mechanical system composed of electromagnetic clutch and gearbox; the control strategy of in-place cleaning of rotor based on process control system is proposed; cleaning of rotor packing during in-place stand-by with ultrasonic cleaning system is implemented; through the joint effect of the above three systems, the rotating packed bed can be switched remotely, and the equipment can be ultrasonically cleaned without affecting the operation, thus ensuring the stable operation of the rotating packed bed for a long period.

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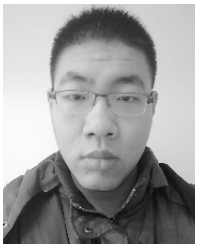

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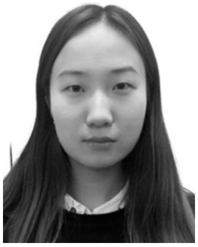

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