Recent advances of annular centrifugal extractor for hot test of nuclear waste partitioning process

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Abstract Advances are being made in the design of the annular centrifugal extractor for nuclear fuel reprocessing extraction process studies. The extractors have been built and tested. Twelve stages of this extractor and 50 stages are used to implement the TRPO process for the cleanup of commercial and defense nuclear waste liquids, respectively. Following advances are available: (1) simple way of assembly and disassembly between rotor part and housing part of extractor, ease of manipulator operation; (2) automatic sampling from housing of extractor in hot cell; (3) compact multi-stage housing system; (4) easy interstage link; (5) computer data acquisition and monitoring system of speed.
Keywords Annular centrifugal extractor, Nuclear waste treatment, Hot test, Automatic sampling

1 Introduction

Solvent extraction equipment has evolved considerably for need of separation of nuclear elements over the last 50 years. Mixer-settler, packed column, pulsed column and centrifugal extractor have been developed in most countries with nuclear fuel reprocessing program.[1] Generally, all types of above extraction equipments are thought to have their advantages and disadvantages. One of them, centrifugal extractor has advantages of high mass transfer efficiency, low liquid holdup, fast startup and shutdown, ease of operation and greater safety with respect to nuclear criticality by virtue of its small compact size. The centrifugal extractor has been developed progressively upon philosophy that the design should be as simple as possible for recent years.

Primary type of centrifugal extractor was derived initially from mixer-settler and built at Savannah River Laboratory (SRL, USA).[2,3,4] The SRL centrifugal extractors have been in use at Savannah River Plant since 1967. The SRL centrifugal extractor has feature of that there is an agitating oar in isolated mixing housing of under extractor. In the late 1960s, a modified centrifugal extractor was developed at Argonne National Laboratory (ANL, USA) while work was being done on the original SRL extractor. The ANL extractor is similar to the SRL extractor except that the air-controlled weir is replaced with a single weir for the heavy phase and that the agitating oar is eliminated, and the liquids are mixed in the annular region between the rotor and its stationary housing. Agitating oar elimination and weir replacement make design simpler. Their immediate advantages are the shortening of shaft and the elimination of a motor with a hollow shaft and the rotary air seal.[5,6] ANL centrifugal extractors are reliable, easy to use, and relatively inexpensive to build, operate, and maintain. ANL extractors are being built, tested and used with the TRUEX process to cleanup nuclear waste. Various TRUEX flowsheets were tested by ANL extractors in laboratory-scale and plant-scale.[7]

Upon application to nuclear fuel reprocessing, details of all equipment concerned, which were built and tested, had been withheld from the literature due to government classification. In the meantime of ANL extractor development, the Institute of Nuclear Energy Technology (INET), Tsinghua University, Beijing, has independently developed annular centrifugal extractor, which is very similar to ANL extractor INET extractors are also used in hydrometallurgy, petrochemical engineering, civil waste water treatment and pharmaceutical chemical engineering as well as nuclear chemical engineering. In particular, TRPO process for cleanup nuclear waste has been developed by

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advantages of INET extractors.[8] Many models of INET annular centrifugal extractor have been built with rotor diameter from ϕ10 mm to ϕ230 mm. Against aggressive matter in extraction process, various types of INET extractor are made of stainless steel, titanium, plastic and glass fibre reinforced plastic. The INET annular centrifugal extractors have been chosen as implementing new solvent extraction process or upgrading existing facilities. In particular, ϕ10 mm INET miniature annular centrifugal extractors had been built more than 200 stages and are very recommendable for research purpose in glovebox and in hot cell. Both laboratories of Karlsrule Nuclear Research Center (CRC, CEC, KFK, Germany) and British Nuclear Fuel Lt (BNFL) are equipped with INET extractors imported from China. 12 stages and 50 stages of ϕ10 mm INET annular centrifugal extractors are used to test the TRPO process flowsheets in hot cell for the cleanup of commercial (in Germany) and defense (in China) nuclear waste liquids respectively. INET annular centrifugal extractors are moved forward to commercialization.

2 Annular centrifugal extractor

A basic diagram of annular centrifugal extractor is shown in Fig.1. The motor drives rotor spin by shaft. Two immiscible liquids flow into the annular mixing zone formed between the spinning rotor and the stationary housing. The liquid-liquid dispersion is created by turbulent flow in the annular mixing zone and flows by gravity to the inlet in the bottom face of the rotor and thus flows into the centrifugal separating zone inside the rotor by miniature different pressure caused by centrifuge between inside and outside of the rotor. In the rotor the dispersion breaks rapidly under the high centrifugal force. The separated phases flow over their weirs and are thrown by centrifugal force from the rotor into their collector rings in the housing. Each liquid leaves its collector ring through a tangential exit port. The cascade extraction flowsheet is formed by links between exit ports and their corresponding inlet ports.

3 Design principle of annular centrifugal extractor

To allow the dispersion to flow by gravity into the rotor, stationary radial vanes attached to the housing and located under the rotor are required to dissipate the rotational velocity of the dispersion. Vanes within the rotor keep the liquids spinning at the same speed as the rotor. Two facts must be considered when designing an extractor. First, the rotor inlet must have a radius somewhat smaller than that of the light phase weir for the dispersed liquids to be pumped through the rotor. Second, the radii for the light and heavy phase weirs must be chosen carefully so that the two vertical surfaces of the dispersion band are located within the separating zone of the rotor, that is, between the light phase weir and the underflow. Phase separation is considered to be satisfactory if each effluent from an extractor stage contains less than 1% volume of the other phase.

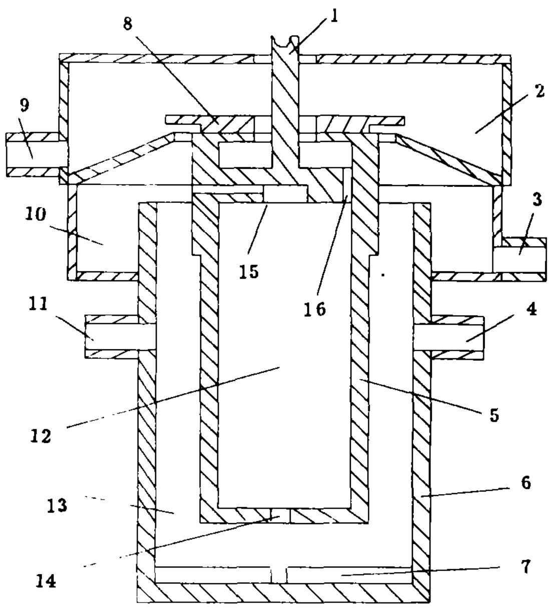

Fig.1 Annular centrifugal extractor

1 shaft; 2 heavy phase collecting ring; 3 light phase exit; 4 heavy phase inlet; 5 rotor (settling zone); 6 stationary housing; 7 radial vanes; 8 heavy hase weir; 9 heavy phase exit; 10 light phase collecting ring; 11 light phase inlet; 12 rotary vanes; 13 mixing zone; 14 rotor inlet; 15 light phase weir; 16 underflow of heavy phase

3.1 Throughput of annular centrifugal extractor

Leonard *et al.*[9] gave the concept of dispersion constant to determine the throughput of annular centrifugal extractor. The dispersion constant $N_{\rm dis}$ is related with intensity of mixing, type of dispersion and system of extraction. The definition is:

$$N_{\rm dis} = \frac{Q}{V}\sqrt{\frac{\Delta Z}{B}} \qquad (1)$$

where Q is the throughput (cm^3/s), V the volume of separation zone (cm^3), ΔZ the width of dispersion in the rotor (cm), $\Delta Z = r_{\rm b} - r_{\rm o}$, $r_{\rm b}$ is the inner radius of rotor (cm), $r_{\rm o}$ the radius of light phase weir (cm), B is the mean acceleration speed of gravity settling (cm/s^2). No matter which extraction system is, $N_{\rm dis}$ can be gotten from batch tests of gravity settling and then the throughput (Q) can be given by gravity settling tests in Eq.(1).

3.2 light and heavy phase weirs

The light and heavy phase weirs of annular centrifugal extractor must be satisfied with the following equation[10]:

$$r_i = \sqrt{\frac{F_{\rm a}R_{\rm a}^2 - (\rho_{\rm o}/\rho_{\rm a})F_{\rm o}R_{\rm o}^2}{1-\rho_{\rm o}/\rho_{\rm a}}} \qquad (2)$$

where r_i is the position of two vertical surfaces of the dispersion band (cm), $F = (r/R)^2$, R is the radius of phase (cm), r is the radius of liquid surface when flowing over the weir (cm). Footnotes 'a' and 'o' represent heavy and light phase respectively. Eqs.(1) and (2) are very fundamental for designing an extractor.

4 Recent advances of annular centrifugal extractor

A more applicable design of extractor should result in lower capital and operating costs, easier manipulation of extractor and extractor which are more reliable and simpler to maintain. For the small volume of solution required in the process of hot test, extractor should be designed as small as possible. So the miniature annular centrifugal extractor with ϕ10 mm rotor has been developed at INET, in which liquid holdup is approximately 4 ml per stage. The extractor possesses advances as followings: simple way of assembly and disassembly between rotor part and housing part in extractor, ease of manipulator operation; automatic sampling from housing of extractor in hot cell; compact multi-stage housing system; easy interstage link; computer data acquisition and monitoring system of speed.

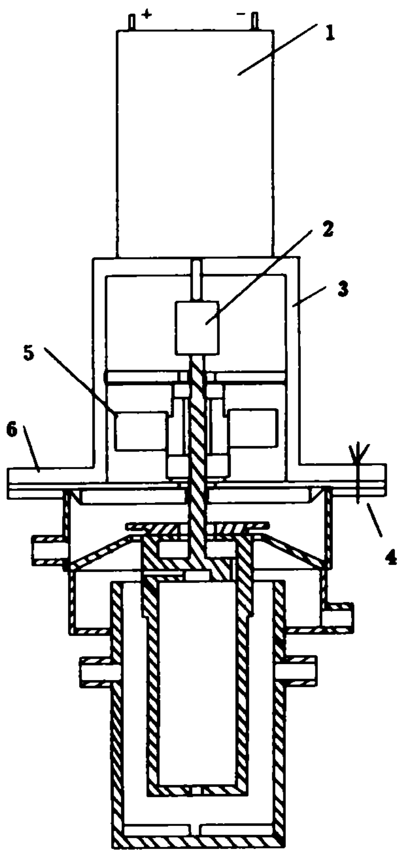

Fig.2 Assembly of ϕ10 mm annular centrifugal extractor

1 motor; 2 coupling; 3 support of motor; 4 screw and nut; 5 housing of bearings; 6 mounting flange

4.1 Improvement of assembly

The assembly schematic of small annular centrifugal extractor is typically shown in Fig.2. All the parts of extractor were welded and threaded together. Flange joint was used to joint rotor part and housing part by screws and nuts. This way of assembly was not easy to operate by manipulator. Because of flange, it is limited to reduce the size of extractor. The extractor of recent design is divided into two parts. One is a housing part shown in Fig.3. The other is a rotor part shown in Fig.4. Two parts are mounted separately, and jointed by cylindrical joint with clearance fit. Surface B is the surface of basic hole and surface A is the surface of shaft with suitable lower deviation. Assembly of extractor is completed by mating of surface A and B. In this way, it is much easy to manipulate extractor in hot cell. Ease is that when rotor part is simply inserted in housing part, assembly of extractor is made. All parts are made within acceptable deviation and are interchangeable. For instance, if one of the motors fails or any other unexpected thing occurs when multi-stage flowsheet is being tested in hot cell. The facility can be fast shut down, then the rotor part with problem can be replaced by manipulator, and facility can be started again soon. The test is continuing. To prevent motor from corrosion of chemical acidic gas, the motor is covered with stainless steel.

4.2 Improved design of housing

To further reduce the liquid holdup of extractor, interstage connection should be reformed. Interstage connection change must be preceded by change of housing design. Two types of housing have been developed for small annular centrifugal extractor. One is called as multi-stage group housing. The other is called as single-stage compact housing. These two types of housing have their own virtue and complement each other. The advances in housing design are discussed as follows.

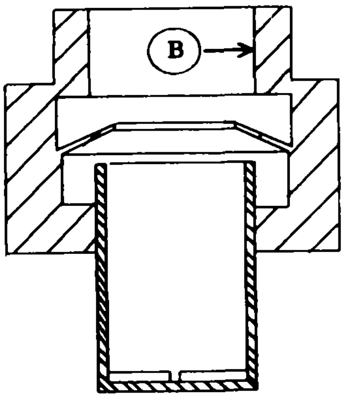

Fig.3 Housing part

Multi-stage group housing is a housing system that contains multiple stage housings (e.g. 4 stages) in a set shown in Fig.5a. The set can theoretically be equivalent to any number stages of extractor. Housing can be a support of extractor. The principal part of the set is a whole stainless steel block, which is machined and consisted of heavy phase collecting rings,

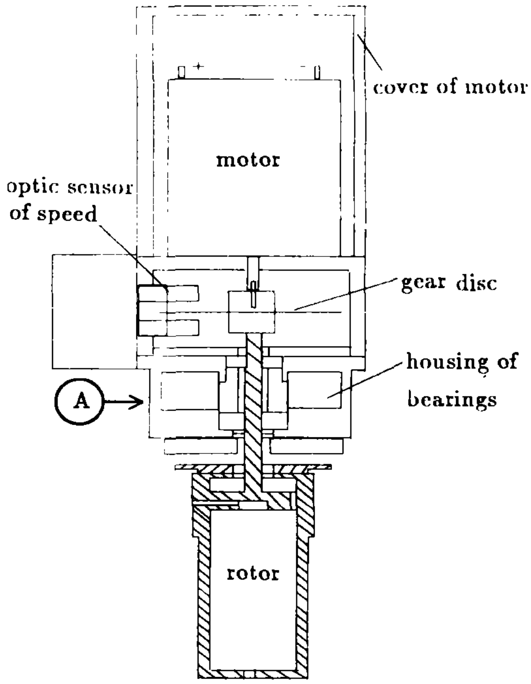

Fig.4 Rotor part

light phase collecting rings and interstage lines. For four stages set of ϕ10 mm rotor extractor, its size is 45 mm wide and 210 mm long. The virtue of this set is no interstage lines between two stages in the set, no risk of leakage in interstage lines, and has very small liquid holdup. The disadvantage of this set is that the number of stage in a set is fixed after extractors being made, and that it is not flexible to meet requirement of extraction flowsheet with different stages of extraction, scrubbing, stripping and cleaning. Because the number of stages in a section and the number of sections can be varied as needed for a particular flowsheet. For example, the clean up of actinides from nuclear waste solutions can make the waste composition vary. In these cases, single-stage compact housing is quite flexible in implementing the required flowsheet for a particular waste.

Single-stage compact housing is shown in Fig.5b. One set contains one stage. The size of a set for ϕ10 mm rotor extractor is 38 mm wide and 40mm long. Housing can also be a support of extractor. There are four holes on the two opposite sides of housing, which are exit and inlet of light and heavy phases, respectively.

Good parallelism and flatness of the two sides are needed to make interstage sealing well. The grooves are designed on the one side to hold sealing gasket made of polytetrafluoroethylene. The interstage seal is shown in Fig.6. The pressures are exerted on the two ends of line formed by extractors. Fifty stages of this extractor had been built and tested, and had implemented TRPO process flowsheet of hot test in hot cell at Tsinghua University. However, the additional small interstage part is needed for stream exit in flowsheet.

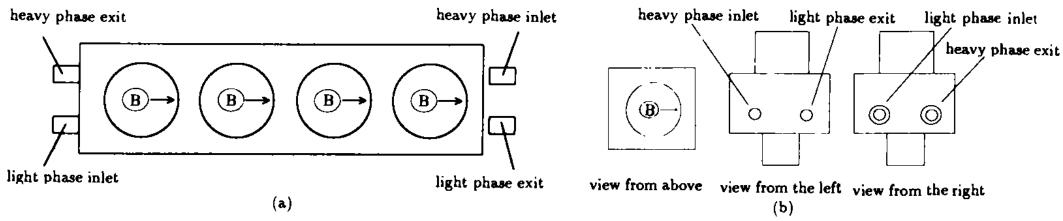

Fig.5 Vertical view of the multi-stage group housing (a) and single-stage compact housing (b)
B is a surface coupled with rotor part

4.3 Sampling from extractor

After a hot test of TRPO process flowsheet in hot cell, liquid left in extractors needs to be sampled for analysis. It is not easy to get samples from many extractors by manipulation. An automatic sampling system is built for TRPO process the hot test. A schematic of sampling unit is shown in Fig.7. The unit is attached to the bottom of extractor housing. When extractors are running, the holes on the extractor bottoms are stopped up by stopper with sealing ring. When sampling, the stoppers are moved down and liquid samples flow out of extractors by gravity. The samples are collected in collecting rings and then flow into sample bottles under the exit ports. The stoppers are driven by manipulator through a sample power transmission mechanism. All bottles of sample are placed on a shuttle plate which moves under extractors on the linear motion antifriction bearing guideway and can be driven by manipulator. The system was tested in TRPO process hot test in hot cell.

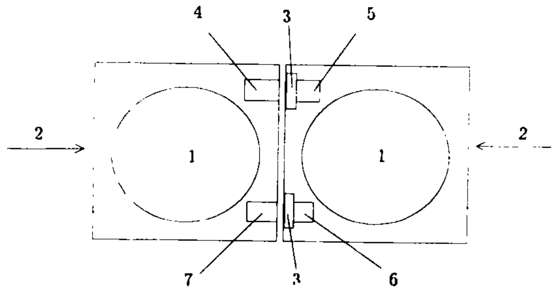

Fig.6 Interstage joint of single-stage compact housing
1 extractor; 2 force; 3 sealing gasket; 4 light phse inlet; 5 light phase exit; 6 heavy phase exit; 7 heavy phase inlet

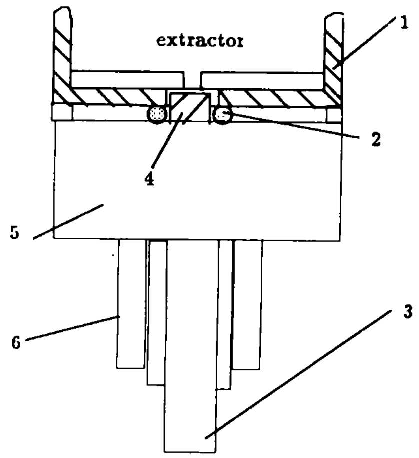

Fig.7 Automatic sampling from extractor
1 housing of extractor; 2 sealing rings; 3 sample exit; 4 stopper; 5 sample collecting ring; 6 linear movement bearing

4.4 Monitoring of motor speed

The rotor of extractor is directly driven by motor, of which speed depends on the voltage of power supply. So the speed of rotor can be simply controlled by changing voltage. For many stages of extractor, such as 50 stages, the personal computer speed acquisition and monitoring system is a practical and necessary way. With the system, the extractors can be remotely controlled and problems can be found outside hot cell in time.

A gear disc is fixed on the coupling of extractor and an optic sensor is installed in extractor as shown in Fig.4. The gear discs are spinning synchronously while rotors are spinning. The optic sensors give out pulse signal, of which frequencies are proportional to the speeds of rotors. The system for speed monitoring is shown in Fig.9. The signals are acquired by computer after amplification, photoelectricity isolation and regulation, and are processed to be speeds of extractors. The computer can find problems in the extractor by change of speed while extractors are running and can give out alarm. The system was tested in TRPO process hot test in hot cell.

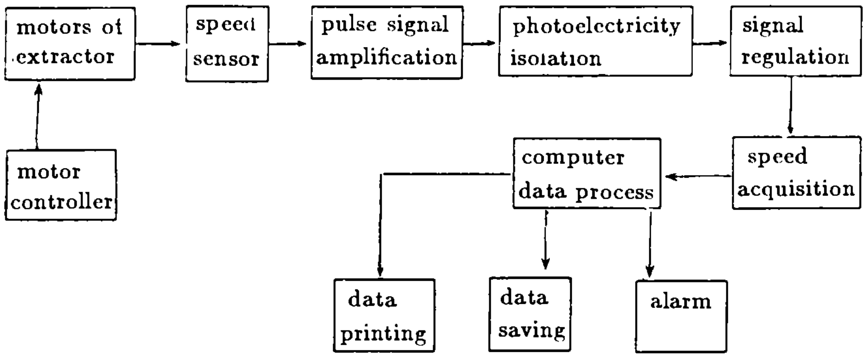

Fig.8 A diagram of speed monitoring

5 Conclusions

Advances in the design of the annular centrifugal extractor continue to be made. The extractors have been improved as follows: (1) simplify the way of operation and maintenance; (2) reduce its size and liquids holdup; (3) be flexible for the variety of process flowsheets; (4) be easy to get sample; (5) allow remote speed monitoring. The INET annular centrifugal extractor with 10mm diameter of rotor is very recommendable when tests of process flowsheets are carried out in glove box and in hot cell.

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