

# An industrial-scale annular centrifugal extractor for the TRPO process

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Received: 29 April 2017/Revised: 19 June 2017/Accepted: 22 June 2017/Published online: 13 March 2018 © Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Chinese Nuclear Society, Science Press China and Springer Nature Singapore Pte Ltd. 2018

Abstract Annular centrifugal extractors (ACEs) offer advantages including excellent hydraulic and mass-transfer performance, small hold-up volume, short residence time, and thus low solvent degradation, high nuclear criticality, easy start-up and shut-down, high compact structure. Therefore, ACEs have attracted increasing interest for future nuclear processing schemes, including the partitioning of high-level liquid waste (HLLW). Laboratoryscale and pilot-scale ACEs have been applied in demonstration tests of the trialkyl phosphine oxide (TRPO) process for HLLW partitioning. In this study, an industrialscale ACE (260 mm in rotor diameter) with magnetic coupling and a "hanging" rotor structure was developed for the TRPO process. Moreover, a series of hydraulic and mass-transfer tests were carried out in the industrial-scale ACE. The maximum throughput can reach 10 m<sup>3</sup>/h under suitable operation parameters when kerosene is used as the organic phase, and water is used as the aqueous phase. The influence of the total flowrate, the flow ratio (aqueous/organic, A/O), and the rotor speed on the liquid hold-up volume was determined. The extraction stage efficiency is higher than 98% under test parameters for extraction of Nd<sup>3+</sup> and HNO<sub>3</sub>, using 30% TRPO kerosene as the

This work was supported by the Program for Changjiang Scholars and Innovative Research Team in University (No. IRT13026), and the National 863 Program for the Nuclear Fuel Cycling and Nuclear Safety Technology Project (No. 2009AA050703).

Wu-Hua Duan dwh203@mail.tsinghua.edu.cn extractant from an HNO<sub>3</sub> solution containing Nd. All results show good performance of the industrial-scale ACE for the TRPO process.

**Keywords** Annular centrifugal extractor · TRPO process · Mass-transfer efficiency · Hydraulic performance · Industrial-scale

# List of symbols

- $C_{A,i}$  Inlet concentration of Nd<sup>3+</sup> or HNO<sub>3</sub> in the aqueous phase (mg/L or mol/L)
- $C_{A,e}$  Equilibrium concentration of Nd<sup>3+</sup> or HNO<sub>3</sub> in the aqueous phase (mg/L or mol/L)
- $C_{A,o}$  Outlet concentration of Nd<sup>3+</sup> or HNO<sub>3</sub> in the aqueous phase (mg/L or mol/L)
- $C_{O,i}$  Inlet concentration of Nd<sup>3+</sup> or HNO<sub>3</sub> in the organic phase (mg/L or mol/L)
- $C_{O,e}$  Equilibrium concentration of Nd<sup>3+</sup> or HNO<sub>3</sub> in the organic phase (mg/L or mol/L)
- $C_{O,o}$  Outlet concentration of Nd<sup>3+</sup> or HNO<sub>3</sub> in the organic phase (mg/L or mol/L)
- $D_{\rm i}$  Inside diameter of the rotor (m)
- g Gravitational acceleration (9.8  $m/s^2$ )
- $h_{\rm b}$  Height of the radial vane (m)
- $\Delta H$  Hydrostatic head (m)
- *L* Length of the rotor settler (m)
- *R* Flow ratio (A/O)
- $r_{\rm A}^*$  Radius of the heavy phase weir (m)
- $R_{\rm h}$  Inside radius of the housing (m)
- $R_{\rm i}$  Inside radius of the rotor (m)
- $r_{\rm m}$  Radius of the rotor inlet (m)
- $r_{\rm O}^*$  Radius of the light phase weir (m)
- $Q_{\rm A}$  Flowrate of the aqueous phase (m<sup>3</sup>/h)
- $Q_{\rm m}$  Maximum throughput (m<sup>3</sup>/h)

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- $Q_{\rm O}$  Flowrate of the organic phase (m<sup>3</sup>/h)
- $Q_{\rm T}$  Total flowrate of both phases (m<sup>3</sup>/h)
- $V_{\rm b}$  Volume of the vertical baffles inside the rotor (m<sup>3</sup>)
- $V_{\rm h}$  Liquid hold-up volume in the housing (m<sup>3</sup>)
- $V_{\rm r}$  Liquid hold-up volume in the rotor (m<sup>3</sup>)
- $V_{\rm r.c}$  Calculated liquid hold-up volume of the rotor (m<sup>3</sup>)
- $V_{\rm t}$  Total liquid hold-up volume (m<sup>3</sup>)
- $V_{\rm w}$  Liquid hold-up volume of the weir section (m<sup>3</sup>)

## **Greek letters**

- $\eta_A$  Extraction stage efficiency for the aqueous phase (%)
- $\eta_{\rm O}$  Extraction stage efficiency for the organic phase (%)
- $\omega$  Rotor speed (r/min)
- $\omega^*$  Angular speed of the rotor (rad/s)

## Abbreviation

A/O	Aqueous phase/organic phase
ACE	Annular centrifugal extractor
ANL	Argonne National Laboratory
GANEX	Group ActiNide EXtraction
DIAMEX	DIAMide EXtraction
DIDPA	DIisoDecylPhosphoric Acid
HLLW	High-level liquid waste
P&T	Partitioning and transmutation
PUREX	Plutonium and uranium recovery by extraction
TODGA	N,N,N',N'-TetraOctyl DiGlycolAmide
TRPO	TRialkyl phosphine oxide
TRUEX	TRansUranic EXtraction

# **1** Introduction

The well-known process of plutonium and uranium recovery by extraction (PUREX) [1] for the separation and recovery of uranium and plutonium from spent nuclear fuel produces large amounts of high-level liquid waste (HLLW). HLLW contains moderate quantities of actinides, as well as fission products including Sr and Cs, which constitutes a permanent hazard to the environment [2, 3]. Recently, the partitioning and transmutation strategy (P&T) that safely treats and disposes of HLLW has attracted increasing interest because it aims to separate long-lived minor actinides (e.g., Am, Np, and Cm) from HLLW and transmute them to short-lived or stable nuclides in a FBR (fast breeding reactor) or ADS (accelerator driven system). This constitutes an advanced nuclear fuel cycle for the sustainable development of nuclear energy [3, 4]. Efficient partitioning of HLLW is vital for the P&T. Various advanced partitioning processes of HLLW based on the solvent extraction method have been developed around the world, e.g., the DIAMEX process [5], the TRUEX process [6], the DIDPA process [7], the TODGA process [8], the GANEX process [9], and the TRPO process [10, 11]. The TRPO process for the efficient partitioning of Chinese HLLW, using 30% TRPO (mixed trialkylphosphine oxide)-kerosene as an extractant, has been studied in China since the early 1980s [12].

In the late 1960s, the annular centrifugal extractor (ACE) was first developed based on the paddle-type centrifugal extractor at the Argonne National Laboratory (ANL), USA [13]. It provides mixing and separation in an extractor [14]. The ACE has some attractive advantages, including excellent hydraulic and mass-transfer performance, small hold-up volume, short residence time, and thus low solvent degradation, as well as low solvent waste generation, high nuclear criticality, easy start-up and shutdown, high compact structure, and thus low construction and operation cost requirements. Therefore, ACEs are favored for future nuclear processing schemes, including the partitioning of HLLW, and have now been widely used in demonstration tests of various HLLW partitioning processes [15, 16]. Since the early 1980s, the Institute of Nuclear and New Energy Technology, Tsinghua University, has been developing ACEs to meet the requirements of demonstration tests for the TRPO process. Both laboratory-scale (10 and 20 mm rotor diameter) [17-19] and pilot-scale (50 and 70 mm rotor diameter) [20] ACEs have been used in various demonstration tests of the TRPO process. 50-stage and 72-stage laboratory-scale ACEs (10 mm rotor diameter) were used for hot demonstration tests of the original total TRPO process in 1996 and the improved total TRPO process in 2009 with real HLLW, respectively [21, 22]. 24-stage pilot-scale ACEs (70 mm rotor diameter) were used in a cold demonstration test of the original total TRPO process with simulated HLLW to verify both the feasibility and reliability of the TRPO process and the adopted separation equipment in 2005 [23]. Meanwhile, laboratory-scale ACEs have also been used in demonstration tests of the simplified PUREX process [24] and Th-based fuel reprocessing [25, 26].

In order to achieve the application of ACEs in the TRPO process on an industrial scale, it is necessary to research and develop industrial-scale ACEs. In this research, an industrial-scale ACE (260 mm rotor diameter) with magnetic coupling and a "hanging" rotor structure has been successfully developed for the TRPO process. A series of hydraulic and mass-transfer tests were performed to evaluate the performance of the industrial-scale ACE.

## 2 Experimental

# 2.1 Chemicals

TRPO was obtained from CYTEC, USA. Its commercial name is Cyanex 923. It mainly comprises four

trialkylphosphine oxides, namely R<sub>2</sub>R'PO (42%), R<sub>3</sub>PO (14%), R'<sub>3</sub>PO (8%), and RR'<sub>2</sub>PO (31%), where R' and R are *n*-hexyl and *n*-octyl groups, respectively [27]. TRPO was diluted with kerosene (Jinzhou Refinery Factory, China) to 30% TRPO kerosene (v/v), and purified before use, as described in a previous study [12]. The viscosity, density, and surface tension of the 30% TRPO kerosene are  $2.82 \times 10^{-3}$  Pa s, 787.8 kg/m<sup>3</sup>, and  $32.35 \times 10^{-3}$  N/m, respectively [28]. HNO<sub>3</sub> and Nd(NO<sub>3</sub>)<sub>3</sub> obtained from Beijing Chemical Works, China, were employed as analytical reagents.

## 2.2 Description of the industrial-scale ACE

The industrial-scale ACE includes four main parts, namely the housing, the rotor, the drive unit, and the motor, as shown in Fig. 1. The rotor's inner diameter is 260 mm. When the rotor speed is 1600 r/min, the relative centrifugal force generated by the spinning rotor is about 372 G. The explosion-proof motor (3-phase 380 V AC, 5.5 kW) is adopted for fire prevention. A magnetic coupling and "hanging" rotor structure are applied in the drive unit of the industrial-scale ACE. The magnetic coupling provides torque to the rotor and enables the motor to be independently and easily replaced [16]. The magnetic coupling and the "hanging" rotor structure provide ease of remote

R <sub>i</sub> (m)	<i>r</i> <sub>m</sub> (m)	<i>L</i> (m)	$r_{\rm O}^*$ (m)	$r_{\rm A}^*$ (m)	<i>R</i> <sub>h</sub> (m)	<i>h</i> ь (m)
0.13	0.044	0.46	0.054	0.065	0.18	0.04

maintenance and a radioactive seal. Table 1 lists the major geometric dimensions of the industrial-scale ACE.

As shown Fig. 1a, immiscible feed liquids with different densities flow into the annular mixing zone through a separate inlet and are then rapidly mixed by the spinning rotor to form a dispersion [29]. In general, the denser phase is the aqueous phase, while the less dense phase is the organic phase. Radial vanes attached to the housing stop rotation of the dispersion when it flows down to the bottom of the housing, and direct the dispersion through the rotor inlet into the rotor. Here, it is accelerated to the rotor speed toward the rotor wall by vertical baffles inside the rotor and quickly separated into two phases by their density difference as it flows upwards under high centrifugal force [30]. The aqueous phase moves toward the peripheral wall of the rotor, while the organic phase is forced to move toward the center of the rotor. The separation rate of the dispersion is a function of the settling velocity under the centrifugal action  $(r\omega^2)$ , the drop size distribution, the surface tensions and





**(b)** 

Fig. 1 (Color online) Sketch (a) and photograph (b) of the industrial-scale ACE

viscosities of the two phases, as well as the density difference between the aqueous and organic phases [31]. Lastly, the separated aqueous and organic phases flow over their respective weirs in the rotor into their respective collectors and tangential outlets in the housing, and flow into adjacent stages or collection vessels by gravity.

#### 2.3 Hydraulic tests

Hydraulic tests of the single-stage industrial-scale ACE were performed using the experimental setup shown in Fig. 2. Here, kerosene was used as the organic phase and deionized water was used as the aqueous phase. The hydraulic performance of the industrial-scale ACE was evaluated by measuring the maximum throughput (sum of the aqueous and organic flowrates) for which the maximum allowable cross-phase entrainment did not exceed 1% at a given rotor speed and flow ratio (aqueous/organic, A/O). Cross-phase entrainment is defined as aqueous phase carryover in the organic effluent stream, or organic phase carryover in the aqueous effluent stream. For most applications, phase separation is generally considered satisfactory if each effluent from the ACE has entrained < 1% of the other phase. This condition results in high stage efficiency [32]. Each effluent stream was collected in a vessel to determine the amount of cross-phase entrainment according to a predetermined time after the industrial-scale ACE reached steady-state operation. After the collected fluid in each vessel was completely separated, the crossphase entrainment in each vessel was measured by volume measurement using a graduated cylinder.

The hydraulic tests were performed with continuous recycling of the two effluent streams to the feed tanks. For each operation, the industrial-scale ACE was first started at the predetermined rotor speed. Then, the aqueous phase



Fig. 2 The setup for both hydraulic performance and mass-transfer tests

was pumped into the industrial-scale ACE at a constant flowrate by a magnetic drive pump (10.8 m<sup>3</sup>/h, 40CQ-20, Shanghai Lian Quan Pump Manufacturing Co. Ltd., China). If the aqueous phase flowed out from the heavy phase outlet, the organic phase was pumped into the industrial-scale ACE at a constant flowrate by another magnetic drive pump. Otherwise, the organic phase flowed out through the heavy phase outlet. The flowrate of each phase liquid was adjusted by the respective rotameter. After the ACE reached steady state, the aqueous and organic effluent streams were sampled and visually examined for cross-phase entrainment. Generally, the operation of the ACE should be close to steady state after three residence times (total liquid hold-up volumes) of the fluid have passed though the ACE (or three total liquid hold-up volumes of the ACE) [32]. In the present hydraulic tests, steady-state operation of the industrial-scale ACE was reached after more than four total liquid hold-up volumes  $(4 \times 0.035 \text{ m}^3)$  of two phases had passed through the ACE. If cross-phase entrainment was < 1% in both collected samples, the flowrate of one phase was kept constant, while the flowrate of the other phase was increased incrementally. These processes were repeated until crossphase entrainment in either effluent stream was > 1%. Later, the flowrate of the phase whose initial flowrate was kept constant was increased to a designed flowrate, and the flowrate of the other phase was incrementally increased. Each time, samples from the effluent streams were collected to check for cross-phase entrainment after reaching steady-state operation. Experiments were carried out for different rotor speeds and flow ratios (A/O). A frequency converter (7.5 kW, Micromaster 420, SIEMENS, Germany) was used to adjust the rotor speed of the ACE and ensure smooth start-up of the motor.

The minimum rotor speed of the ACE operation was determined according to the following equation [33]:

$$\Delta H = \frac{\left(\frac{2\pi\omega}{60}\right)^2}{2g} \left(r_{\rm O}^{*2} - r_{\rm m}^2\right). \tag{1}$$

For the industrial-scale ACE, when  $\Delta H$  is equal to the rotor length,  $\omega$  is the minimum rotor speed, namely, 990 r/min. However, considering mass-transfer efficiency, the normal rotor speed should be higher than the minimum rotor speed.

The liquid hold-up volume affects the interfacial area, mixing, and mass-transfer efficiency of the ACE [29], which depends on rotor speed, total flowrate, rotor geometry, and housing geometry. The liquid hold-up volume in both the rotor and the housing of the industrial-scale ACE was determined by a liquid discharging method [34]. Firstly, when the industrial-scale ACE reached steady state, the liquids in the housing were drained into a vessel by opening the discharge valve under the housing bottom after the pumps were stopped. Secondly, the motor was shut down to stop rotation of the rotor, and the liquid in the rotor was drained into another vessel. Lastly, volumes of the two phases in each vessel were determined after complete settling of the dispersion using a measuring cylinder. Tests for obtaining the liquid hold-up volume were performed for different rotor speeds, total flowrates, and flow ratios.

#### 2.4 Mass-transfer tests

In the TRPO process, 30% TRPO kerosene can efficiently extract trivalent actinides and lanthanides from HLLW. Trivalent actinides and lanthanides have similar chemistry, so extraction of trivalent actinides (Am) can be simulated by extraction of Nd<sup>3+</sup> from HNO<sub>3</sub> solution using 30% TRPO kerosene in the experimental studies. The mass-transfer efficiency of the industrial-scale ACE was evaluated by extracting Nd<sup>3+</sup> and HNO<sub>3</sub> from HNO<sub>3</sub> solution containing Nd<sup>3+</sup> using 30% TRPO kerosene. The setup for mass-transfer tests is the same as that for hydraulic tests (Fig. 2). For each test, the aqueous phase was first pumped by a magnetic drive pump at a constant flowrate into the industrial-scale ACE, and the organic phase was then pumped by another magnetic drive pump at a constant flowrate into the industrial-scale ACE. Each time, the flowrate of each effluent stream was measured to obtain the exact flowrate of each phase. Samples for Nd<sup>3+</sup> and HNO<sub>3</sub> concentration analysis were taken from each effluent stream after the ACE reached steady-state operation. For calculating the extraction stage efficiency of the industrial-scale ACE, two phase feeds were equilibrated at a determined phase ratio by violently mixing them to obtain equilibrium concentrations of both the aqueous and organic phases. The Nd<sup>3+</sup> concentration of the aqueous phase was obtained by ICP-AES (Inductive Coupled Plasma). The Nd<sup>3+</sup> concentration of the organic phase was obtained by firstly stripping with 5.5 mol/L HNO<sub>3</sub> three times, and then analyzing the Nd<sup>3+</sup> concentration of the stripping solution by ICP-AES [20]. The HNO<sub>3</sub> concentrations of the organic and aqueous phases were obtained by titration using a standard NaOH solution, and K<sub>2</sub>C<sub>2</sub>O<sub>4</sub> was added as the masking agent. Both the initial  $Nd^{3+}$  and HNO<sub>3</sub> concentrations of the organic phase were 0, while the initial Nd<sup>3+</sup> and HNO<sub>3</sub> concentrations of the aqueous phase were 97.5 mg/L and 0.5 mol/L, respectively. The Murphree extraction stage efficiency relationship was used to express the mass-transfer efficiency as follows [33]

$$\eta_{\rm A} = \frac{(C_{\rm A,i} - C_{\rm A,o})}{(C_{\rm A,i} - C_{\rm A,e})} \times 100\% \quad \text{(for the aqueous phase)},$$
(2)

$$\eta_{\rm O} = \frac{(C_{\rm O,o} - C_{\rm O,i})}{(C_{\rm O,e} - C_{\rm O,i})} \times 100\% \quad \text{(for the organic phase)}.$$
(3)

Mass-transfer tests were conducted for different flow ratios (A/O), rotor speeds, and total flowrates.

#### **3** Results and discussion

## 3.1 Hydraulic performance

#### 3.1.1 Maximum throughput

The maximum throughput  $Q_{\rm m}$  of the ACE was estimated by the following equation [33]

$$Q_{\rm m} = 1.386 \times 10^{-4} \omega D_i^2 L. \tag{4}$$

For the industrial-scale ACE,  $\omega$  is 1600 r/min,  $D_i$  is 26 cm, and L is 46 cm, so  $Q_m$  is approximately 6.9 m<sup>3</sup>/h. Effects of the flow ratio (A/O) on the throughput of the industrial-scale ACE at different rotor speeds are presented in Fig. 3. The single-stage hydraulic performance of the industrial-scale ACE is excellent. The maximum throughput can reach 10 m<sup>3</sup>/h for a kerosene-water system at a rotor speed of 1600 r/min, which is higher than the estimated value (approximately 6.9 m<sup>3</sup>/h). The maximum throughput varies with the flow ratio (A/O) at a defined rotor speed. The normal limit to the ACE throughput is determined by the thickness of the dispersion band in the rotor (Fig. 1). This band is actually a hollow dispersion cylinder. At a given rotor speed, the dispersion band thickness increases as total flowrate increases until, at the



Fig. 3 (Color online) Effects of flow ratio on the throughput of the industrial-scale ACE at different rotor speeds

maximum throughput, the dispersion band reaches either the light phase weir (with subsequent appearance of the aqueous phase in the organic effluent stream) or the underflow (with subsequent appearance of the organic phase in the aqueous effluent stream) [13]. The flow ratio (A/O) has an important effect on the ACE throughput. As the flow ratio (A/O) decreases, the liquid height over the light phase weir increases, while the liquid height over the heavy phase weir decreases. This shifts the dispersion band outward from the light phase weir to the aqueous underflow. Thus, at high flow ratios (A/O), phase entrainment (when the maximum throughput is exceeded) will be due to the aqueous phase in the organic effluent stream. At low flow ratios (A/O), phase entrainment (when the maximum throughput is exceeded) will be due to the organic phase in the aqueous effluent stream. At intermediate flow ratios (A/ O), the full volume of the separating zone will be used, and both effluent phases will experience other-phase entrainment at the same time if the maximum throughput is exceeded. At this flow ratio (A/O), the ACE capacity is at a maximum. It is also observed that, with an increase in rotor speed, the maximum throughput increases at the same flow ratio (A/O), because the increase in rotor speed enhances separation of the two phases due to the increased centrifugal force.

The maximum throughput differs for different extraction systems. A good engineering design practice is to keep the nominal throughput in an ACC to no more than 67% of the nominal maximum throughput [32, 35]; thus, the industrial-scale ACE can reach 7 m<sup>3</sup>/h for a 30% TRPO-kerosene-HNO<sub>3</sub> solution system, which is almost equal to the estimated value (about 6.9 m<sup>3</sup>/h).

#### 3.1.2 Liquid hold-up volume

After obtaining the liquid hold-up volume in the housing  $(V_{\rm h})$  and the rotor  $(V_{\rm r})$ , the sum of  $V_{\rm h}$  and  $V_{\rm r}$  is the total liquid hold-up volume  $(V_{\rm t})$  of the industrial-scale ACE. The  $V_{\rm r}$  including the liquid hold-up volume in both the weir section  $(V_{\rm w})$  and the rotor settler (Fig. 1) can also be obtained by calculating the following relationship [29]:

$$V_{\rm r,c} = V_{\rm w} + \left[ \pi L \left( R_{\rm i}^2 + \frac{gL}{\omega *^2} - r_{\rm O} *^2 \right) - V_{\rm b} \right].$$
(5)

The influence of operation parameters on  $V_h$ ,  $V_r$ , and  $V_t$ , as well as  $V_{r.c.}$ , are shown in Table 2. The  $V_r$  remains almost constant (about 23.0 L), i.e.  $V_r$  does not change with the flow ratio (A/O), the total flowrate, or the rotor speed.  $V_h$  decreases with an increase in rotor speed, but increases with an increase in total flowrate. The effect of flow ratio (A/O) on  $V_h$  is not clear. The effect of flow ratio (A/O), rotor speed, and total flowrate on  $V_t$  are the same as those on  $V_h$ . Table 2 also presents the calculated liquid hold-up volume in the rotor ( $V_{r,c}$ ) using Eq. (5). All  $V_r$  values are higher than  $V_{r,c}$ , because Eq. (5) does not consider the influence of some important parameters, including the flow ratio (A/O), the total flowrate, and the physical properties of the extraction system on the  $V_r$ .

## 3.2 Mass-transfer efficiency

During mass transfer, the dispersed phase is converted into small droplets by inputting the mixing energy in the form of shear caused by the differential velocity between inner and outer layers of the annular mixing zone. As the bulk dispersed phase is converted into small drops, the surface area available for mass transfer increases several times. Generally, the higher the rotor speed, the higher the mass-transfer efficiency. Tables 3 and 4 present the extraction stage efficiency of the single-stage industrialscale ACE for extracting Nd<sup>3+</sup> and HNO<sub>3</sub>, respectively. In all tests, the extraction stage efficiencies are more than 98%. It is clear that excellent phase mixing is achieved, even at relatively low rotor speed. The mass-transfer efficiency of the ACE is also a complex function of various operating variables such as rotor speed, total flowrate, and interfacial tensions between the two phases [37]. The interfacial tension changes with the flow ratio (A/O). Generally, a lower total flowrate, lower flow ratio (A/O), or higher rotor speed results in an increased extraction efficiency [20].

The residence time in the mixing chamber varies from 18 s to 5 s. These test results demonstrate that equilibrium in Nd and HNO3 extraction is rapidly attained. Moreover, no clear trends are observed according to rotor speed, total flowrate, or flow ratio (A/O). The data show good masstransfer efficiency in the industrial-scale ACE. There are two possible explanations for extraction stage efficiencies over 100%. One may be analytical errors, and the other may be the large flowrate of each phase making it difficult to precisely control each flowrate. Accordingly, the phase ratio used to obtain the equilibrium concentration is inconsistent with the actual flow ratio. Compared with the laboratory-scale ACE (20 mm rotor diameter) used for extracting Nd<sup>3+</sup> from HNO<sub>3</sub> solution containing Nd<sup>3+</sup> [36], and the pilot-scale ACE (70 mm rotor diameter) used for extracting HNO<sub>3</sub> from HNO<sub>3</sub> solution with 30% TRPO kerosene [20], the extraction stage efficiency of the industrial-scale ACE for extracting Nd<sup>3+</sup> and HNO<sub>3</sub> with 30% TRPO kerosene from nitric acid solution containing  $Nd^{3+}$  is higher. The mixing intensity experienced by the liquid in the mixing zone is proportional to the power consumption per unit of annular volume. Generally, the larger the ACE, the greater power consumption per unit of annular volume [37]. Thus, the mixing intensity of the two phases in the industrial-scale ACE is higher than that in

**Table 2** Influence of operation parameters on  $V_{\rm r}$ ,  $V_{\rm h}$ , and  $V_{\rm t}$ 

ω (r/min)	$Q_{\rm A}$ (m <sup>3</sup> /h)	$Q_{O}$ (m <sup>3</sup> /h)	$Q_{\rm T}$ (m <sup>3</sup> /h)	<i>R</i> (A/O)	$\frac{V_{\rm h}}{({\rm m}^3)} \times 10^{-3}$	$\frac{V_{\rm r}}{({\rm m}^3) \times 10^{-2}}$	$V_{\rm r,c}$ (m <sup>3</sup> ) × 10 <sup>-2</sup>	$ \begin{array}{c} V_{\rm t} \\ ({\rm m}^3) \times 10^{-2} \end{array} $
1450	1.56	1.52	3.08	1.03:1	8.68	2.297	2.131	3.165
1450	2.03	2.07	4.10	1:1.02	8.92	2.304	2.131	3.196
1450	2.60	2.52	5.12	1.03:1	9.33	2.294	2.131	3.227
1450	2.95	3.02	5.97	1:1.02	9.85	2.309	2.131	3.294
1450	3.59	3.43	7.02	1.05:1	10.2	2.306	2.131	3.326
1450	1.36	2.62	3.98	1:1.93	9.06	2.312	2.131	3.218
1450	1.02	2.95	3.97	1:2.89	8.94	2.308	2.131	3.202
1450	2.69	1.38	4.07	1.95:1	9.12	2.304	2.131	3.216
1450	2.98	1.10	4.08	2.71:1	9.05	2.306	2.131	3.211
1300	1.94	2.02	3.96	1:1.04	9.31	2.310	2.131	3.241
1600	2.01	1.96	3.97	1.03:1	8.76	2.292	2.130	3.168

 Table 3 Influence of operation parameters on the extraction stage efficiency for extracting Nd

ω (r/min)	$Q_{\rm A}$ (m <sup>3</sup> /h)	Qo (m <sup>3</sup> /h)	$Q_{\rm T}$ (m <sup>3</sup> /h)	<i>R</i> (A/O)	$\eta_{\mathrm{A}}$ (%)	η <sub>0</sub> (%)
1450	0.85	0.97	1.82	1:1.14	99.1	99.3
1450	1.36	1.42	2.78	1:1.04	100.7	98.3
1450	1.88	2.11	3.99	1:1.12	104.1	101.8
1450	2.63	2.88	5.51	1:1.10	100.1	101.1
1450	3.19	3.23	6.42	1:1.01	99.2	100.2
1450	1.42	2.65	4.07	1:1.87	99.2	99.8
1450	0.98	2.95	3.93	1:3.01	101.5	99.7
1450	2.43	1.30	3.73	1.87:1	100.2	102.3
1450	3.05	0.97	4.02	3.14:1	99.5	99.9
1300	1.84	2.05	3.89	1:1.11	99.6	101.6
1600	1.85	2.08	3.93	1:1.12	99.2	100.4

Table 4 Influence of operation parameters on the extraction stage efficiency for extracting  $\mathrm{HNO}_3$ 

ω (r/min)	$Q_{\rm A}$ (m <sup>3</sup> /h)	$Q_{\rm O}$ (m <sup>3</sup> /h)	$Q_{\rm T}$ (m <sup>3</sup> /h)	<i>R</i> (A/O)	$\eta_{\mathrm{A}}$ (%)	η <sub>0</sub> (%)
1450	0.85	0.97	1.82	1:1.14	98.4	98.3
1450	1.33	1.42	2.75	1:1.07	99.0	101.8
1450	1.88	2.11	3.99	1:1.12	100.9	101.4
1450	2.56	2.73	5.29	1:1.07	100.2	102.5
1450	3.19	3.23	6.42	1:1.01	100	100
1450	1.42	2.65	4.07	1:1.87	99.8	99.5
1450	0.98	2.95	3.93	1:3.01	100.5	103.2
1450	2.43	1.30	3.73	1.87:1	99.3	98.6
1450	3.05	0.97	4.02	3.14:1	99.8	100.2
1300	1.84	2.05	3.89	1:1.11	99.7	99.0
1600	1.85	2.08	3.93	1:1.12	99.5	102.6

both the laboratory-scale and pilot-scale ACEs. In addition, the volume fluctuations in the larger ACE are much smaller relative to the total liquid volume than in the smaller ACE, particularly the laboratory-scale ACE (20 mm rotor diameter).

# 4 Conclusion

An industrial-scale ACE (260 mm rotor diameter) with magnetic coupling and a "hanging" rotor structure has been successfully developed for the TRPO process. Moreover, test results show that the industrial-scale ACE had good hydraulic performance and mass-transfer efficiency. The suggested operation regime for 30% TRPOkerosene-HNO<sub>3</sub> solution, when the diameter of the heavy phase weir is 130 mm, is a rotor between 1300 and 1600 r/ min, a flow ratio (A/O) between 1/5 and 5/1, and a total flowrate between 0.2 and 6 m<sup>3</sup>/h. Moreover, when the diameter of the heavy phase weir is varied, the suggested operating regime will vary accordingly. During the entire test duration, the industrial-scale ACE was stable with no interruption in operation. This also showed that the design of the magnetic coupling is reliable. Further research into design improvements will be performed with the aim of achieving remote operation and maintenance, extended service life, minimized maintenance downtime, greater reliability, and clean-in-place of solids in the rotor so that it can be applied to the TRPO process on an industrial scale in future.

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