EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Rotating Packed Beds (RPBs)

TECHNOLOGY CODE:

AUTHOR: Jian-Feng Chen, Beijing University of Chemical Technology, China

Table of contents

1. Technology

1.1 Description of technology / working principle

(Feel free to modify/extend the short technology description below)

Rotating packed beds (RPBs), also called high gravity or HiGee technology, are rotating devices which create a high gravity environment simulated by the action of centrifugal force. This technology was originally invented by Dr. Colin Ramshow and his co-workers in 1979 for the separation processes (Ramshaw and Mallinson, 1979). As one of the cutting-edge process intensification technologies, RPBs has received considerable attention and was extensively explored for applications in absorption, stripping, distillation, heat transfer, adsorption, liquid-liquid extraction, crystallization, reaction and so on (Trent, 2004).

The structure of a typical countercurrent RPB is illustrated in Fig. 1. The key part consists of a packed rotor (2), which is mounted on a shaft, and filled with high specific area packing. Liquid, or slurry is introduced into the eye space of the rotor from a liquid inlet pipe (8) to spray onto the inside edge of the rotor through a slotted pipe distributor (4). The liquid entering the bed flows radially outwards under the influence of centrifugal force, passing through the packing and outside space between the rotor and the casing (5), to finally collect and leave the RPB via a liquid outlet (6). Gas is introduced from a gas inlet (1) to flow radially inwards through the packing and exits from a gas outlet (7). Liquid and gas flow countercurrently and mix vigorously in the packing of the rotor.

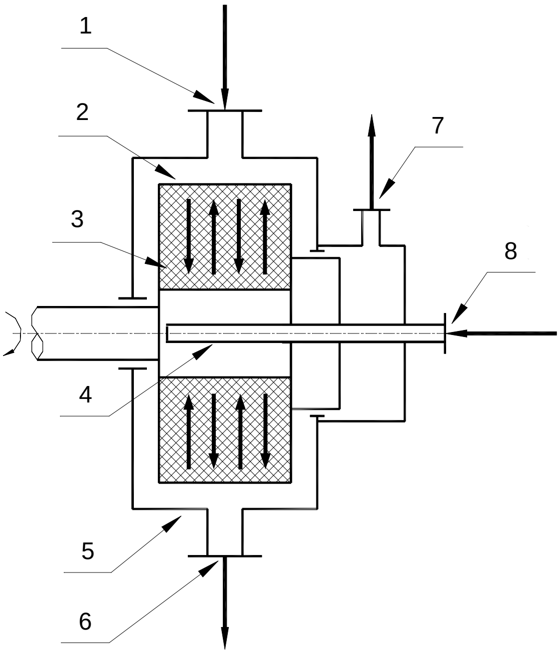

Fig. 1. The structure of a countercurrent RPB (1) gas inlet; (2) rotor; (3) packing; (4) liquid distributor; (5) shell; (6) liquid outlet; (7) gas outlet; (8) liquid inlet

The high gravity environment in RPBs could be orders of magnitude larger than gravity on the earth and cause liquid going through the packing in RPB to be spread or split into micro or nano droplets, threads or thin films, thus significantly intensifying mass transfer and micromixing up to 1-3 orders of magnitude larger than that in a conventional packed bed.

RPBs hence demonstrate the following unique characters: 1) mass/heat transfer and micromixing intensified significantly; 2) equipment volume and weight shrunk markedly; 3) short residence time of substances in RPB (100 ms - 1 s).

1.2 Types and “versions”

(Describe the most important forms/versions of technology under consideration, including their characteristic features, differences and similarities)

There are three types of RPBs in terms of the ways of fluid mixing in RPBs:

Countercurrent RPB:

As shown in Fig. 1, liquid flows radially outwards under the action of high gravity while gas flows inwards in a countercurrent RPB. Therefore. Liquid and gas contact countercurrently in the packing.

Cocurrent RPB:

Cocurrent RPBs are usually employed in systems consisting only of liquid fluids, which are introduced into the RPB via liquid inlets and distributors. Two or more liquid fluids flow radially outwards under the action of high gravity and mix cocurrently in the packing (Fig. 2).

Cross-flow RPB:

In a cross-flow RPB, liquid, like in other types of RPBs, flows radially outwards through the packing, whereas gas flow axially through the packing. Therefore, liquid and gas mix cross-currently in the packing (Fig. 3).

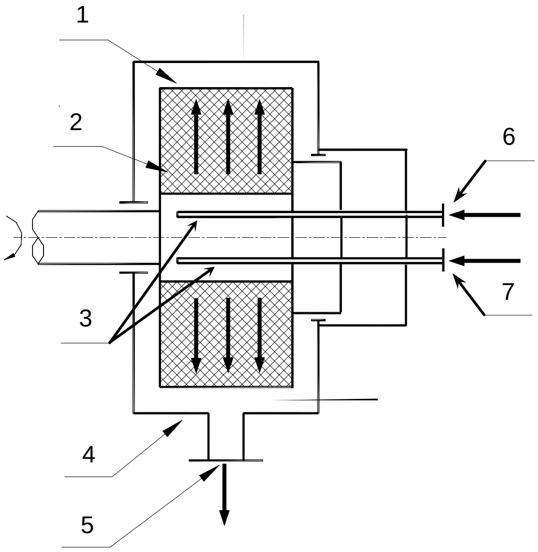

Fig. 2. Cocurrent RPB
(1) rotor; (2) packing; (3) liquid distributors; (4) casing; (5) liquid outlet; (6), (7) liquid inlets

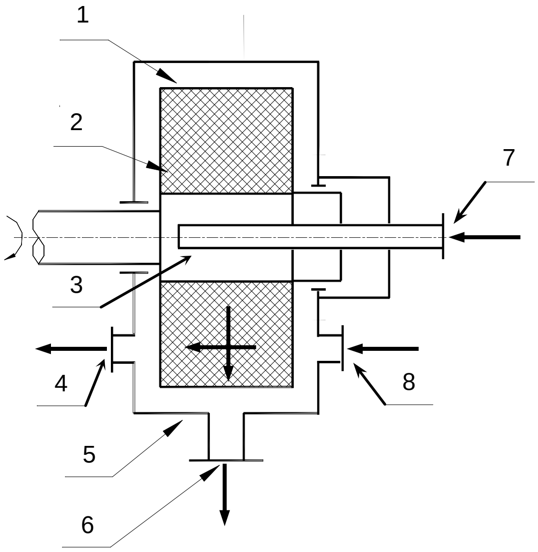

Fig. 3. Cross-flow RPB
(1) rotor; (2) packing; (3) liquid distributor; (4) gas outlet; (5) casing; (6) liquid outlet; (7) liquid inlet; (8) gas inlet

Cocurrent RPBs are used for liquid systems, while countercurrent RPBs and cross-flow RPBs are applied to liquid and gas systems. Cross-flow RPBs exhibit advantages of reduced rotor diameter and no countercurrent flooding, as well as shortcomings of lower mass transfer driver, longer axial length and liquid entrainment in the exit gas in comparison with countercurrent RPBs, which are thus a preferred choice in this field.

1.3 Potency for Process Intensification: possible benefits

(In Table 1 describe the most important documented and expected benefits offered by the technology under consideration, focusing primarily on energy; CO_2 emission and costs, providing quantitative data, wherever possible. Add other benefits, if needed).

Table 1: Documented and expected benefits resulting from technology application

Benefit	Magnitude	Remarks
Better product quality	Particle size reduced for 4- to 6-fold	In the syntheses of ultrafine particles or nanoparticles, RPBs exhibit unique advantages due to significantly intensified micromixing and mass transfer, e.g. ● Smaller particle size, 15-30 nm $CaCO_3$ nanoparticles ● Uniform particle size distribution and controllable morphologies
Increased yield/selectivity	Up to 10% -30%	It was reported that intense mass transfer capability of RPBs allowed 10% higher yields and 50% reduction in stripping gas for the production of HOCl as compared to conventional spray tower operation. It is also expected that RPBs will boost the yield by 30% in a methylene diphenyl diisocyanate (MDI) production line (240K tons/y).
Higher process efficiency	Reaction time shortened for 2- to 3-fold	In the synthesis of $CaCO_3$ nanoparticles, reaction time in RPBs is 15-25 min, while it takes 60-75 min in conventional stirred tank or bubbling reactor.
Smaller reactor volume	Reactor volume shrunk up to 80%	In the application of RPBs for HOCl production, $CaCO_3$ nanoparticles synthesis and seawater deaeration, reactor volumes were reduced by 80%, 70% and 70% respectively, compared to conventional vessels.
Cost savings	Up to 70%	In the application of RPBs for HOCl production and seawater deaeration, capital investment was saved by 70% and 35% respectively due to smaller equipment volume. Cost savings can also result from faster processing, higher product yield, less raw materials consumption, lower operating cost and better product quality.
Energy savings	Up to 30%	In the production of overbased petroleum calcium sulfonate (OPCS) lubricating oil detergent and lubricant additives dispersed with copper nanoparticles, energy savings reached 30%.
CO_2 emission reduction	Up to 20%	CO_2 emission reduced by 20% in the production of OPCS lubricating oil detergent by RPBs. A reduction in waste generation can also be expected to reach 75% and 50% respectively in the production of lubricant additives

		dispersed with copper nanoparticles and MDI.

1.4 Stage of development

After several decades of development, RPBs have already come into commercial applications successfully in seawater deaeration, HOCl production, nanoparticles syntheses.

RPBs are currently under extensive exploration for applications in absorption, stripping, distillation, heat transfer, adsorption, extraction, reaction and crystallization etc. Most of these works are in the lab-scale so far and some of them are in the pilot trial period.

2. Applications

2.1 Existing technology (currently used)

(Describe technology (-ies) that are conventionally used to perform the same or similar operations as the PI-technology under consideration)

RPBs can be applied to mass transfer or/and heat transfer or/and micromixing-limited systems and the combination of unit operations in one device. Conventional technologies used for these systems involve stirred tank reactor, bubbling reactor, reaction tower, electrochemical reactor, absorber, desorber, evaporator, mixer, centrifuge, stripper, distiller/rectifier, separator, chemical heat pump, heat exchanger and so on.

2.2 Known commercial applications

(Is the technology broadly applied on commercial scale? In which process industry sectors is the technology most often applied: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? What is the estimated number of existing applications? In Table 2 provide the most prominent examples of realized applications and provide their short characteristics)

Several commercial applications of the RPBs have been reported, as shown in the following table.

Table 2. Industrial-scale applications of the Technology (existing and under realization)

Sector	**Company - Process/Product name/type**	**Short characteristic of application**	**Production capacity /Plant size**	**Year of application**	**Reported effects**
Specialty chemicals & pharma	Guangdong Guangping Chemical Co., Ltd, China -Nanosized $CaCO_3$	RPBs were employed to react $Ca(OH)_2$ with CO_2 in order to produce $CaCO_3$ nanoparticles	3,000 t/y	2000	• 15-30 nm in particle size; • 2 to 3 times shorter reaction time; • 70% smaller reactor volume
Specialty	Inner Mongolia	Same as	3,000	2001	Same as above

chemicals & pharma	Mengxi High-Tech Materials Co., Ltd, China -Nanosized $CaCO_3$	above	t/y		
Specialty chemicals & pharma	Shanxi Huaxin Nanomaterials Co., Ltd, China -Nanosized $CaCO_3$	Same as above	10,000 t/y	2001	Same as above
Specialty chemicals & pharma	Anhui Chaodong NanoMaterial Science & Technology Co., Ltd, China -Nanosized $CaCO_3$	Same as above	10,000 t/y	2002	Same as above
Specialty chemicals & pharma	Shandong Shengda Nanomaterials Co., Ltd, China -Nanosized $CaCO_3$	Same as above	10,000 t/y	2002	Same as above
Specialty chemicals & pharma	Petroleum China Corporation, Karamay Petrochemical Co., China -Overbased petroleum calcium sulfonate lubricating oil detergent	RPBs were employed to react $Ca(OH)_2$ with CO_2 in order to produce in situ mono-dispersed $CaCO_3$ nanoparticles in the lubricating oil detergent	1,000 t/y	2007	• 10-20 nm in $CaCO_3$ size; • 2 to 3 times shorter reaction time; • 20% less raw materials; • 30% less energy; • 20% less CO_2 emission
Specialty chemicals & pharma	Petroleum China Corporation -Copper nanoparticles lubricant additive	Mono-dispersed Copper nanoparticles were produced by RPBs	100 t/y	2006	• 2-15 nm in size • 25% less raw materials; • 30 less energy; • 75% less waste generation
Specialty chemicals & pharma	Dow Chemical Co. -HOCl production	RPBs were employed for HOCl production coupling the reaction and stripping processes	150 t/h (based on raw NaOH solution)	1999	• 10% higher yield; • 50% less stripping gas; • 30% less operating cost; • 70% less capital cost; • 80% smaller reactor volume
Petroleum	Shengli Oil Field Co., China -Seawater deaeration	RPBs were used to remove oxygen from	Two 250 t/h installations	1998	• 35% less capital cost; • 70% smaller reactor volume

		the flooding water			

2.3 Known demonstration projects

(Are there any demonstration projects known related to the technology under consideration? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 3 provide the short characteristics of those projects.)

There is one pilot-scale RPB installation for the production of pharmaceutical nanopowder which can be seen as a demonstration project.

Table 3. Demonstration projects related to the technology (existing and under realization)

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of application	Reported effects
Specialty chemicals & pharma	NCPC Beta Co., Ltd, China -Amorphous cefuroxime axetil nanoparticles	RPB was employed as a precipitator to produce nanosized cefuroxime axetil nanoparticles	40 t/y	• 300-400 nm in particle size, 20 times less than those by spray drying crystallization; • ~ 50% higher dissolution rate and solubility (better bioavailability)

2.4 Potential applications discussed in literature

(Provide a short review, including, wherever possible, the types/examples of products that can be manufactured with this technology)

Numerous researches on RPBs have been reported and there exist several good reviews on this subject (see further). These works focus principally on the mass transfer and /or micromixing-limited systems. Enhancement effects of RPBs have been reported in the following fields:

- Absorption: SO_2, CO_2 removal from vent gases; NH_3 absorption; H_2S separation from CO_2.
- Stripping: O_2 removal from water; stripping of residual monomer and solvent from polymers; air stripping of volatile organic compounds from groundwater, wastewater or gas streams; stripping of NH_3 from wastewater.
- Adsorption: ion exchange; volatile organic removal from water; recovery of proteins; fine chemicals production.
- Distillation: separation of methanol/ethanol mixture, ethanol/propanol mixture, cyclohexane/toluene mixture, cyclohexane/n-heptane mixture.
- Liquid-liquid extraction: penicillin recovery; extraction of trace contaminants from water.

- Crystallization: production of nanoparticles.
- Reaction: ozonation; polycondensation; polymerization; fermentation; HOCl production.
- Electrochemical cell: removal of gas bubbles from the electrodes.
- Dedusting and demisting: oil separation from gas.
- Heat transfer: heat exchanger; seawater desalination; heat pump.

3. What are the development and application issues?

3.1 Technology development issues

(In Table 4 list and characterize the essential development issues, both technical and non-technical, of the technology under consideration. Pay also attention to "boundary" issues, such as instrumentation and control equipment, models, etc.) Also, provide your opinion on how and by whom these issues should be addressed)

Table 4. Technology development issues

Issue	Description	How and by whom should be addressed?
Packing materials and configuration	Packed rotor is the core part of RPB. Packing materials should be selected discreetly and packing configuration should be studied thoroughly in terms of various systems to optimize the mass/heat transfer and micromixing efficiency	R&D projects carried out at the universities, in collaboration with packing producers and RPB manufacturers
Reliability of industrial scale RPB device	Although there are several successful application examples, the long-term reliability of the large scale RPB device is still unknown and a chief concern of potential users	R&D projects carried out at the universities, in collaboration with RPB manufacturers and application company
Modeling and scale-up methodologies	The scale-up of RPB is mostly empirical presently. Fundamental performance characterizations and more generalized theoretical expressions for RPB parameters that accurately predict performance on a wide range of rotor designs and sizes will be needed to confidently scale-up this technology	R&D projects carried out at the universities, in collaboration with RPB manufacturers and application company

3.2 Challenges in developing processes based on the technology

(In Table 5 list and characterize the essential challenges, both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Table 5. Challenges in developing processes based on the technology

Challenge	Description	How and by whom should the challenge be addressed?
Reliability	The major objections to the use of RPBs have been associated with the risks of scale-up and the operation of rotating equipment	This challenge can be addressed by obtaining considerable commercial experience via a long-term operation of RPBs

Cost	Another challenge is with the cost of the operation of rotating equipment. Cost may result from the energy consumption of driving the rotor, structure complexity and maintenance	This challenge should be addressed in the R&D projects on an overall consideration of cost resulting from the replacement of conventional technologies with RPBs

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 6)

Table 6. Key publications on the technology

Publication	Publication type (research paper/review/book/ report)	Remarks
Ramshaw, C., 1983, Higee distillation – an example of process intensification, Chem. Eng., 389: 13-14	Research paper	First paper in the field
Zeng, C., Guo, K., Song, Y. H., Zhou, X. M., Ai, D. G., 1997, Industrial practice of Higravitec in water deaeration. In: Semel, J., (ed), 2nd International Conference on Process Intensification in Practice, BHR Group, London, England, 273-287	Research paper	First paper reporting on industrial practice of RPB application
Chen, J. F., Wang, Y. H., Jia, Z. Q., Zheng, C., 1997, Synthesis of nanoparticles of $CaCO_3$ in a novel reactor. In: Semel, J., (ed), 2nd International Conference on Process Intensification in Practice, BHR Group, London, England, 157-164	Research paper	First English paper reporting on nanoparticles syntheses by RPB technology
Trent, D., Tirtowidjojo, D., Quarderer, G., 1999, Reactive stripping in a rotating packed bed for the production of hypochlorous acid. In: Green, A., (ed), 3rd International Conference on Process Intensification for the Chemistry Industry, BHR Group, London, England, 217-231	Research paper	First paper reporting on industrial practice of bulk chemicals (HOCl) production by RPBs
Chen, J.F., Wang, Y.H., Guo,F., Wang,X.M., Zheng, C., 2000, Synthesis of Nanoparticles with Novel Technology: High-gravity Reactive Precipitation, Ind. Eng. Chem. Res.,39,948-954	Research paper	Key general paper reporting syntheses of nanoparticles including principles and methodology suitable for liquid-liquid, gas-liquid and gas-liquid-solid multiphase systems
Chen, J. F., Guo, K., Guo, F., Zhang, P. Y., Shao, L., Song, Y. H., Wu, W., Chu, G. W., 2002, High gravity technology and application – a new reaction and separation technology, Chemical Industry Press, Beijing, China	Book	The only monograph about RPBs so far (In Chinese)
Chen, J. F., Shao, L., 2003, Mass production of nanoparticles by High Gravity Reactive Precipitation Technology with low cost, China Particuology, 1(2): 64-69	Review	Overview of inorganic nanoparticles production by RPBs
Trent, D., 2004, Chemical processing in high-gravity fields. In: Stankiewicz, A., Moulijn, J. A.	Book chapter	Overview of the fundamental

(ed.), Re-engineering the chemical processing plant: Process intensification, Marcel Deckker, New York, USA, 33-67		researches, applications and commercial examples of RPBs
Rao, D. P., Bhowal, A., Goswami, P. S., 2004, Process Intensification in Rotating Packed Beds (HIGEE): An Appraisal, Ind. Eng. Chem. Res. 43: 1150-1162	Review	Overview of the fundamental researches on RPBs
Yun, J., Chen, J. F., 2006, Higee heaven, The Chemical Engineer, 8: 36-38	Review	Overview of nanosized $CaCO_3$ and nanoscale pharmaceuticals production
Zou, H. K., Shao, L., Chen, J. F., 2006, Progress of higee technology – from laboratory to commercialization, J. Chem. Ind. Eng. (China), 57(8): 1810-1816	Review	Overview the applications of RPBs in precipitation, reaction and separation processes (In Chinese)

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 7. Under "remarks" provide, where applicable, the names/types of products targeted by the given patent.)

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
US 4283255: Mass transfer process	ICI PLC (GB)	For the intensification of fluids mass transfer
US 4,382,045: Centrifugal gas-liquid contact apparatus	ICI PLC (GB)	Structure improvement
US 4,382,900: Centrifugal gas-liquid contact apparatus	ICI PLC (GB)	Structure improvement
US 4,400,275: Mass transfer apparatus and process	ICI PLC (GB)	For the intensification of fluids mass transfer
US 4,627,890: Centrifugal device	ICI PLC (GB)	Structure improvement for distillation
US 4,687,585: Separation process utilizing centrifugal rotor	ICI PLC (GB)	For crude oil stabilization or dehydration or natural gas drying
US 4,692,283: Centrifugal gas-liquid contact apparatus	ICI PLC (GB)	Structure improvement
US 4,715,869: Degassing of liquids	ICI PLC (GB)	For degassing of liquids, especially deaeration of water
US 4,770,753: Electrochemical cell	ICI PLC (GB)	For electrochemical reaction
US 5,084,249: Rotary centrifugal contactor	British Nuclear Fuels PLC	For liquid-liquid extraction
US 5,363,909: Compact contacting device	Praxair Technology, Inc.	Structured packing for mass or heat transfer
US 6,045,660: Mechanically assisted		For the rectification of

two-phase contactor and fuel ethanol production system		liquid mixtures, the scrubbing of gases, the evaporation of liquids, and the condensation of vapors to the liquid state
US 6,048,513: Method for synthesis of hypohalous acid	The Dow Chemical Co.	For the synthesis of hypohalous acid
US 6,827,916: Method of making silica	Beijing University of Chemical Technology	For the synthesis of silica nanoparticles
US 6,884,401: Method for removing volatile components from a high viscosity liquid by using rotation pack bed	Industrial Technology Research Institute	For the removal of volatile components from liquid
US 6,893,754: Fuel cell system with device for water recovery and method of operating such a system	Daimler Chrysler AG	For water recovery by absorption/ desorption
EP0002568: Mass transfer apparatus and its use	ICI PLC (GB)	For the intensification of fluids mass transfer
EP0020055: Process and apparatus for effecting mass transfer	ICI PLC (GB)	For the intensification of fluids mass transfer
EP0023745: Process and apparatus for effecting mass transfer	ICI PLC (GB)	For the intensification of fluids mass transfer
EP0024097: Apparatus and process for treating a fluid material while it is subjected to a centrifugal force.	ICI PLC (GB)	Structure improvement
EP0047085: Centrifugal gas-liquid contact apparatus	ICI PLC (GB)	Structure improvement
EP0053881: Mass transfer apparatus	ICI PLC (GB)	For the intensification of fluids mass transfer
EP0080328: Centrifugal device	ICI PLC (GB)	Structure improvement for distillation
EP0084410: The removal of hydrogen sulphide from gas streams	ICI PLC (GB)	For H_2S removal
EP0089128: Process for displacing dissolved gas from water	ICI PLC (GB)	For the removal of dissolved gas from water
EP0204193: Process and apparatus for separating CO_2 from gases	Man Technologie GMBH (DE)	Structure improvement
EP0343802: Rotary centrifugal contactor	British Nuclear Fuels PLC	For liquid/liquid extraction processes
WO9404266: Separation of aqueous and organic components	University of Newcastle	For the removal of organic components from an aqueous stream
WO2005039731: Spinning impingement multiphase contacting device	Cleveland Gas Systems LLC	For heat or mass transfer
~~US 6827916: Method of Making Silica~~	~~Beijing University of Chemical Technology~~	~~For the synthesis of silica nanoparticles 前面已经列出该专利~~
China ZL 92102061.9: Deaeration ~~M~~method of ~~deaeration of~~ oilfield flooding water	Beijing University of Chemical Technology	For deaeration of oilfield flooding water
China ZL95105344.2: Preparation method of ultrafine particles	Beijing University of Chemical Technology	For the preparation of ultrafine and nano-particles

China ZL 95105343.4: Preparation method of ultrafine $CaCO_3$	Beijing University of Chemical Technology	For the synthesis of ultrafine $CaCO_3$ ~~nano~~particles
China ZL 95215430.7: ~~强化传递反应的旋转床超重力场装置 Apparatus for rotation pack bed for effecting mass transfer and reaction by using a centrifugal force~~Rotating packed bed apparatus for intensifying transfer and reaction	Beijing University of Chemical Technology	For the intensification of fluids mass transfer
China ZL 95107423.7: ~~错流旋转床超重力场装置 Apparatus for tolerant-flow rotation pack bed by using a centrifugal force~~Cross-flow rotating packed bed apparatus	Beijing University of Chemical Technology	Structure improvement
China ZL 98126371.2: ~~超细氢氧化铝的制备方法~~ Preparation method of ultrafine $Al(OH)_3$	Beijing University of Chemical Technology	For the synthesis of $Al(OH)_3$ ultrafine- and nano-particles
China ZL 00100355.0: ~~一种连续法制备沉淀碳酸钙的方法~~ A continuous - preparation method of precipitated $CaCO_3$	Beijing University of Chemical Technology	For the continuous synthesis of precipitated $CaCO_3$ particles
China ZL 01141787.0: ~~一种纳米氢氧化镁阻燃材料制备新工艺~~ A novel preparation process of ~~preparing~~ nano-sized ~~Al~~Mg(OH)~~$_3$~~$_2$ ~~used for~~ flame-retardant ~~materials~~	Beijing University of Chemical Technology	For the synthesis of ~~flame-retardant~~ $Mg(OH)_2$ nanoparticles as flame-retardant
China ZL 03128673.9: ~~一种制备微粉化硫酸沙丁胺醇的方法 A~~ Preparation method of ~~preparing~~ ultrafine salbutamol sulfate powders	Beijing University of Chemical Technology	For the ~~synthesis~~ preparation of ~~salbutamol sulfate ultrafine particles~~ ultrafine pharmaceutical powders
China ZL 01819843.0: ~~一种超细的改性氢氧化铝及其制备方法 A method of preparing~~ Modified ultrafine ~~modified~~ $Al(OH)_3$ and preparation method thereof	Beijing University of Chemical Technology	For the synthesis of modified ultrafine $Al(OH)_3$ ~~ultrafine~~ particles
China ZL 91109255.2: Rotating packed bed apparatus for intensifying transfer and reaction ~~旋转床超重力场强化传递与反应装置 Apparatus for rotation pack bed for effecting mass transfer and reaction~~	Beijing University of Chemical Technology	For the intensification of gas-liquid mass transfer
China ZL 93104828.1: ~~好气菌的繁殖或好气发酵的方法~~ Method of propagating aerobic bacteria and the aerobic fermentation	Beijing University of Chemical Technology	For the propagation of aerobic bacteria and for the aerobic fermentation
China ZL 91111028.3: ~~转动布液式旋转床装置 Rotational liquid-distribution apparatus for rotation pack bed~~Rotating packed bed apparatus with rotational liquid distributor	Beijing University of Chemical Technology	Structure improvement
China ZL 92100093.6: ~~带有抽吸装置的旋转床超重力场装置 Rotational liquid-distribution apparatus for rotation pack bed~~Rotating packed bed	Beijing University of Chemical Technology	Structure improvement

apparatus with sucking device		
China ZL 91229204.0: Rotating packed bed apparatus for effecting transfer and reaction 旋转床超重力场传递与反应装置 Apparatus for rotation pack bed with an aspirator device by using a centrifugal force	Beijing University of Chemical Technology	Structure improvement
China ZL 03123308.2: 超重力反应结晶法制备纳米硫化锌 A high gravity reactive crystallization method of preparing for the preparation of nano-sized ZnS	NMTNanoMaterails Technology Pte Ltd; Beijing University of Chemical Technology	For the synthesis of ZnS nanoparticles 注：NMT 为第一申请单位
China ZL 200410037885.9: 高碱值磺酸钙润滑油清净剂的制备方法 Preparation method of overbased calcium sulfonate lubricating oil detergenthigh-alkali-value calcium sulfonate lube detergent	克拉玛依市金山石油化工有限公司; 北京化工大学 Jinshan Petrochemical Co. Ltd; Beijing University of Chemical Technology	For the synthesis of high-alkali-value calcium sulfonate lube detergentpreparation of overbased calcium sulfonate lubricating oil detergent
China ZL 02132373.9: 制备钛酸锶粉体的方法 PrepatarionPreparation method of $SrTiO_3$ powdersparticles	Beijing University of Chemical Technology	For the synthesis of $SrTiO_3$ particles 以上为授权专利
WO 0294715: 一种超细氢氧化铝，其制备方法，由其得到的超细改性氢氧化铝产品及其制备方法 A new method for preparing ultra-fine aluminium hydroxide & preparation and modification of ultrafine aluminium hydroxideUltrafine aluminum hydroxide and preparation method thereof, and modified utrafine aluminum hydroxide and preparation method thereof	Beijing University of Chemical Technology	For the synthesis of ultra-fine aluminium hydroxide and modified aluminium hydroxide 注：WO 表示是 PCT 申请
WO 2004028971: Method for synthesis of strontium titanate powder	Beijing University of Chemical Technology	For the synthesis of strontium titanate powder
WO 2004076379: A process for preparing crystalline perovskite-type compound powders	NanoMaterails Technology Pte Ltd; NMT; Beijing University of Chemical Technology	For the synthesis of crystalline perovskite-type compound powders
US 10/624944: A high gravity reactive precipitation process for the preparation of barium titanate powders	Beijing University of Chemical Technology	For the synthesis of barium titanate powders
China 02156507.4: Method for catalytic reaction	China Petroleum & Chemical Corporation;中国石油化工股份有限公司 中国石油化工股份有限公司 Beijing University of Chemical Technology	Structure improvement
China 200310101838.1: Method for of removing impurity components from gas phase	China Petroleum & Chemical Corporation 中国石油化工股份有限公司 中国石油化工股份有限公司 Beijing University of	For the removal of impurity components from gas phase

	Chemical Technology	
China 200310103434.6: A type reaction facility-rotating packed bed mass transfer technologyHigh gravity rotating bed apparatus for effecting mass transfer and reaction	China Petroleum & Chemical Corporation;中国石油化工股份有限公司中国石油化工股份有限公司 Beijing University of Chemical Technology	For the intensification of fluids mass transfer
China 200410086342.6: Preparation method of ultrafine silica particles powders by reaction sulfate sulfuric acid precipitation methodreaction	Beijing University of Chemical Technology	Structure improvement For the preparation of ultrafine particles
China 200510088834.3: Technology and set-upProcess and apparatus for alkylation reaction catalyzed by ionic liquid	Beijing University of Chemical Technology	For alkylation reaction
China 200510130561.4: Technological methodProcess for the liquid phase oxidation of cylcohexane oxidation with liquid phase to cyclohexanone	Beijing University of Chemical Technology	For cylcohexane oxidation to cyclohexanone
China 01122413.4: 反应沉淀法制备超细高纯碳酸钡 Preparation of ultrafine barium carbonate with high purity by reactiveon precipitation method	Beijing University of Chemical Technology	For the synthesis of barium carbonate with high purity
China 01145312.5: 制备具有具体形态的碳酸钙的方法 Method for preparation of Calcium Carbonate with concrete patternPreparation method of calcium carbonate with different morphologies	Beijing University of Chemical Technology	For the synthesis of calcium carbonate with concrete pattern with various morphologies
China 02105383.9:一种微细晶须状碳酸钙的制备方法 A new method for the preparation of Calcium Carbonate fine whiskerPreparation method of fine wiskers of calcium carbonate	Beijing University of Chemical Technology	For the synthesis of fine whiskers of calcium carbonate fine whisker
China 02127654.4: 头孢拉定晶体以及制备头孢拉定的方法 Preparation and crystal structure of cefradineCefradine crystals and the preparation method thereof	Beijing University of Chemical Technology	For the synthesis preparation of cefradine particles
China 02145860.X: 一种纳米二氧化钛的制备方法 A route to preparation methods for nanosized titaniaPreparation method of nanosized titania	Beijing University of Chemical Technology	For the synthesis of nanosized titania
China 03106771.9: 一种制备各种晶态钙钛矿类化合物粉体的方法 A new method for the preparation of perovskite compounds with all kinds of CrystallinePreparation method of perovskite compound powders with various crystal structures	Beijing University of Chemical Technology	For the synthesis of perovskite compounds
China 03157555.2: 一种超重力-超临界反应/结晶装置及其应用/结晶工艺 Process and apparatus for effecting high gravity and supercritical reaction	Beijing University of Chemical Technology	Structure improvement

and crystallizationing ~~by supergravity supercritical reaction technique~~		
China 200410069398.0: ~~一种无定型头孢呋辛酯的制备方法~~ Preparation~~A~~ method of ~~preparing~~ amorphous cefuroxime axetil~~ester~~	Beijing University of Chemical Technology	For the ~~synthesis~~ preparation of ~~amorphous cefuroxime ester~~pharmaceutical ultrafine powders

4.3 Institutes/companies working on the technology

(Provide the list of most important research centers and companies in Table 8)

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
University of Newcastle upon Tyne (Prof. Colin Ramshaw)	United Kingdom	Inventor of RPB. Focus shifted to other types of reactor, like spinning disc reactor, in recent years
Beijing University of Chemical Technology (Prof. Jian-Feng Chen)	China	Broad range of research activities. Realized successful commercial applications of RPBs for nanoparticles synthesis and seawater deaeration
NanoMaterials Technology Pte Ltd. (Dr. Jimmy Yun)	Singapore	New processes, nanomaterials and products development using RPBs for pharmaceutical and special chemical industries
Indian Institute of Technology (Prof. D. P. Rao)	India	Focus on fundamental research and structure improvement
Chang Gung University, National Taiwan University, National Tsing Hua University, Industrial Technology Research Institute (Prof. Hwai-Shen Liu and Prof. Chia-Chang Lin)	Taiwan, China	Focus on fundamental research and applications in wastewater treatment

5. Stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers in Table 9)

There are no regular suppliers or developers available for RPBs for the time being, since this technology has not enjoyed wide market acceptance yet. The existing commercial- and lab-scale RPBs were manufactured by a collaboration of universities and contracted mechanical factories.

Table 9. Supplier and developers

Institute/Company	Country	Remarks

5.2 End users

(Describe the existing and potential end-users, other than those already listed in Table 2)

Potential group of end users includes companies operating in the pharmaceutical sector for the production of nanodrugs and companies with concerns of wastewater and/or flue gas control. Conventional chemical industry with desire for combined unit operations may also see this technology as a good choice.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

RPBs exhibit unique features in the intensification of mass/heat transfer and micromixing, and several successful industrial applications have been found in China and USA. This technology may show special advantages when unit operations are combined in one RPB device. However, extensive market acceptance of RPB is yet to come due to concerns related to long-term reliability and energy cost of rotating equipment, which will be relieved by long-time running of RPBs to gain substantial commercial data and experience. Applications of this technology in a large scale necessitate sound theoretical foundations which should be achieved by comprehensive fundamental researches on RPB parameters like packing structure, fluid flow, mass/heat transfer, micromixing, pressure drop, residence time, flooding, power and their influence on the reactions and separation processes.