EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:

ROTATING ANNULAR CHROMATOGRAPHIC REACTOR

TECHNOLOGY CODE: 2.2.3.2

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1. Technology

1.1 Description of technology / working principle

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

The reactive chromatography (*RC)* is a process integrating the chemical or biochemical reaction together with chromatographic separation. Such integrated process, carried out in a single apparatus (chromatographic reactor), offers the opportunity to overcome a chemical equilibrium of the reversible reactions as well as to improve an efficiency of separation. This method can be especially attractive as alternative to reactive distillation, if the components involved are non-volatile or temperature sensitive as are often encountered in biotechnology and pharmaceutical industry. However, due to the same operating conditions applied for reaction and separation in the chromatographic reactor, an efficient operating range of these conditions can be limited (Strohlein et al., 2005).

It is important to distinguish between the processes carried out in chromatographic reactors (*CR*) and in adsorptive reactors (*AR*), because in both types of reactors a chemical reaction is integrated with a separation by adsorption. The reactive adsorption performed in adsorptive reactors is a typical cyclic process, in which the adsorbent must be regenerated after its saturation with one of the reactant. While in chromatographic reactors, the sorption-desorption processes are sequentially repeated during the flow of eluent along the reactor bed, so a cyclic regeneration of the adsorbent is in this case not necessary. The adsorptive reactors are usually applied at the elevated temperature and in the systems with gaseous reactants, while the chromatographic reactors at the moderate temperature and in the liquid systems.

The advantages of *RC* - in comparison to a conventional reaction-separation process carried out sequentially first in the reactor, then in the adsorber - have been proved experimentally and widely discussed in the literature – e.g. see Ganetsos et al., 1993, Sardine et al., 1993, Coca et al., 1993, Lode et al. (2001), Strohlein et al., 2005.

The following reactions should be mentioned as representative examples used for investigations of *RC* process:

- reversible esterification - e.g. production of β-phenethyl acetate – Kawase et al. (1996), ethyl acetate – Mazzotti et al. (1996), Mazzotti et al. (1997), methyl acetate - Lode et al. (2001), Strohlein et al. (2004), Yu et al. (2003), glycerol triacetate – Gelosa et al. (2003), Lang (2003),
- hydrolysis reaction (hydrolysis of methyl formate) - Wetherold & Wissler (1974), Cho et al. (1980a, 1980b), Carr (1993), Falk et al. (1999),
- eterification (MTBE synthesis) – Zhang et al. (2001, 2002),
- alkilation (production of bisphenol A) – Kawase et al. (1999),
- acylation (diethylacetal synthesis) – Silva & Rodrigues (2005),
- glucose isomerisation (production of high-fructose syrup) – Hashimoto et al. (1983), Toumi & Engell (2004), Borges et al. (2005, 2006), Zhang et al. (2004),
- sucrose inversion – Ganetsos et al. (1993), Sarmidi & Barker (1993), Mauer et al. (1996), Azevedo et al. (2001), Minceva & Rodrigues (2005),
- lactose hydrolysis – Shieh & Barker (1996),

- lactosucrose production – Kawase et al. (2001),
- regioselective enzymatic esterification – Meissner & Carta (2002),
- partial oxidation of methane to methanol – Tonkovich et al. (1994), Bjorklund & Carr (2002),
- hydrogenation of 1,3,5-trimethylbenzene (mesitylene) – Ray & Carr (1995).

Almost all of the reactions listed above are carried out in the liquid – solid system, while only the methane oxidation and the hydrogenation of MES are performed in the gas-solid system. Most of these reactions are carried out with use of the ion-exchange resins, which act simultaneously as the catalyst and the adsorbent. In some systems the reaction is carried out in the fluid phase with use of the homogeneous catalyst dissolved in eluent (hydrolysis of the methyl formate) or with the enzyme suspended in the eleuent (sucrose inversion).

In the simplest way, the reactive chromatography processes can be carried out in a single reactor column with pulse injection of the substrate(s). In this case, for the reversible reaction: A↔ C + D, a schematic diagram of concentration profiles of compounds A, C and D along the column length are shown in Fig. 1. Flowing along the reactor column, the reactant A is converted into the products (C and D), which are simultaneously separated. A removal of the products from the reaction zone helps to increase the substrate conversion above the equilibrium one, while practically pure products can be collected at the reactor outlet. The reactive chromatography process operated following the batch mode (a single column with pulse dosing of the substrate) can be only used for process investigation and has no a practical application. It is due to a high eluent requirement, high product dilution and inefficient use of the stationary phase. To increase its productivity, the reactive chromatography has to be carried out in a continuous process.

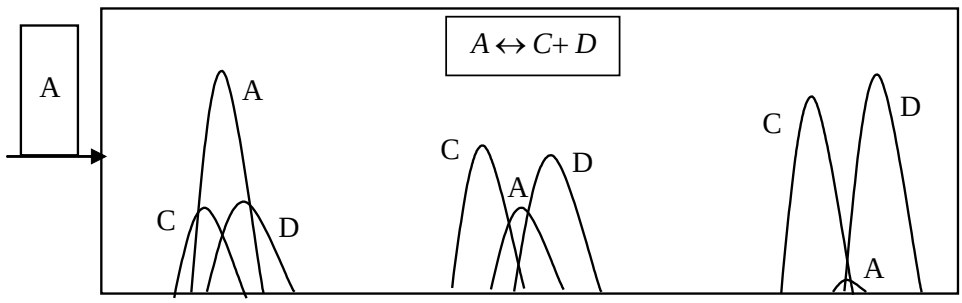

Fig. 1. Reactants concentrations along the column length.

Taking into account technologies originated from a purely separative chromatography, two types of continuous reactive chromatography processes are employed: counter-current processes, in which the solid phase moves counter currently to the flow direction of liquid and a co-current process, in

which common velocity components of the solid and the liquid phases can be distinguished.

In the former method, different technical implementations can be found such as: a true countercurrent chromatographic reactor (*TCCR*), where the solid phase is continuously moved as well as a simulated moving bed reactor (*SMBR*), in which a movement of the solid and liquid phases is simulated by periodically switching the inlet and outlet ports. Because a practical implementation of the *TCCR* concept causes serious technical problems, the simulated moving bed technology is frequently employed – e.g. see Lode *et al.* (2001), Strohlein et al. (2005). In the latter (co-current) method the most well-known implementation is the rotating annular chromatographic reactor (*RACR*). Application of the annular chromatographic reactors (*RACR*) is especially favorable for the reacting systems with multiple (more than two) products and for several reactions carried out simultaneously.

1.2 Types and "versions"

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

The principles of operation of the rotating annular chromatographic reactor (*RACR)* can explained for the reversible second order reaction, which is representative for numerous processes carried out in chromatographic reactors and is described with the following stoiochiometric equation: A + B ↔ C + D.

In practice, very often one of the reactants - say B – is used as the eluent, so it is in a large excess and changes in its concentrations can be neglected. In this case the above mentioned stoichiometric equation becomes equivalent to the simplified one: A ↔ C + D.

In the annular chromatographic reactor the solid phase is placed between two concentric cylinders, which can rotate with a constant angular velocity (ω) around their common axis – see a schematic diagram of *RACR* reactor shown in Fig. 2.

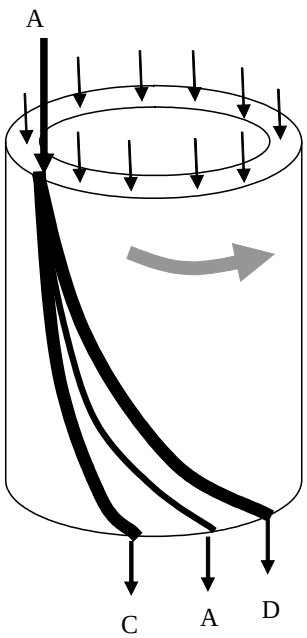

Fig. 2. Schematic diagram of rotating annular chromatogramphic reactor (RACR).

A type of packing used to form the reactor packed bed depends on the reacting system involved in the performed process. The solid phase usually consists of the mixture of grains being the catalyst pellets and the adsorbent particles, respectively. In this case the heterogeneous reaction takes place at the active centers of the catalyst, while the adsorption on the on the adsorbent grains. In many cases an integrated packing, which grains serve simultaneously as the catalyst and the adsorbent, is utilized. For the reacting systems with a homogeneous catalyst dissolved in the eluent, the solid phase consists of the adsorbent only.

The eluent is fed from the top of the reactor and is equally distributed over the annular reactor inlet, while the reactant A (or for more complex reactions a mixture of reactants) is introduced via a single stationary inlet nozzle. A migration of reactants occurs due to a vertical flow of the liquid eluent along the reactor bed and a horizontal movement of the solid phase. Therefore, the reacting species with a low affinity to the adsorbent travel with a low horizontal and high vertical velocity component, while for species with a high affinity to the solid phase a horizontal velocity component becomes significant. In such a system all conditions of the reactive chromatography are fulfilled: a removal of reaction products from the reaction zone helps to increase the conversion, while due to a chromatographic separation practically pure products can be collected at different angular positions of the reactor outlet.

To avoid an inconvenient implementation of the construction described above construction, in which a rotated annular bed can cause problems with efficient sealing, a different concept is often employed in a laboratory and preparative practice. In this improved version of *RACR* the annular bed is kept fixed, while the dosing nozzle (feed) and also collectors of each product are rotated with the same constant angular velocity (ω). The main advantages of this improved construction, when it is compared to the conventional one in which the annular bed is rotated, can be listed as follows: - the power input for rotation can be saved, since a heavy mass forming the bed does not have to be rotated, - scaling up of the reactor with a fixed bed is easier, - the bed can be easily kept at a required temperature because of a thermostatic jacket installed in this case is possible (Goto & Takahashi, 1993).

Both types of *RACRs* constructions have originated directly from the continuous rotating annular chromatography (separation process without involving the chemical reaction). In fact the chromatographic separation and the reactive chromatography can be carried out in the same apparatus.

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
Energy savings	No data available	Significant energy savings are expected due to increased yield and selectivity as well as better product quality
Less CO2 emission	No data available	Due to energy savings
Cost savings	No exact data available	Significant reduction of cost is expected due to integration of reaction and separation: - reduction of investment costs as for each integrated process (even up to 60-70 %) - reduction of operating costs due to elimination of additional processes concerning sequential separation processes (e.g. solvents recovery) - better environment protection due to process integration
Increased yield/selectivity	Conversion increase up to 20-30 %	Improved conversion of reactants, due to a possibility of complete conversion even for reversible reactions. Improved selectivity due to a chromatographic separation of products.
Better product quality	No data available	Due to involving a chromatographic separation high quality (purity) products can be obtained. It is particularly essential when other separation methods are ineffective.

It should be pointed out that the benefits listed above are common for all reactive chromatography processes carried out in the simulated moving bed reactors (*SMBRs*) as well as in the rotating annular chromatographic reactors (*RACRs*). In general a reactive chromatography should be used for reacting systems, where application of less sophisticated and cheaper methods (e.g. reactive distillation) is impossible or ineffective due to non-volatility or thermal instability of the products as well as their physico-chemical similarity (identity).

The benefits which are specific for *RACR*s, in comparison to SMBRs, concern a possibility of carrying out the reactive chromatography process for the reacting systems with multiple reactions and the number of products larger than two. Because in a case of RACRs a specific consumption of the eleunet is larger than for SMBRs, therefore application of RACRs is particularly attractive for the systems where a cheap eluent can be used.

1.4 Stage of development

Application of *RACR*s in a preparative and laboratory scale is very well described and documented in the literature, while there is no data on a practical application of RACRs in industry.

The laboratory and preparative equipment is offered (see further), which can be used for carrying out a simple chromatographic separation as well as for a reactive chromatography.

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)

Processes involving a chemical or biochemical reaction and a downstream processing, which consists of chromatographic separation (purification), are frequently carried out sequentially – i.e. first the reaction is performed in the reactor, then the postreacting mixture is treated in the chromatographic separator (purificator). In comparison to the integrated processes, where both component processes (reaction and separation) are carried out simultaneously in one apparatus, these sequential method is less effective.

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)

Industrial applications of *RACR*s are not known, while only the preparative and/or laboratory reactors are used. A comprehensive review of a history as well as a characterization of some most important constructions applied to carry out a preparative continuous annular chromatographic separation is given in the paper by Uretschläger & Jungbauer, 2002. In many other papers a use of the home made *RACR* equipment is reported.

Only the process of simultaneous biochemical reaction and chromatographic separation of products – a sucrose inversion described by Sarmidi & Barker (1993) - can be considered as the process carried out in a pilot plant scale. The used apparatus was in this case as long as 1.4 m, however an annular volume of the active bed was rather moderate (14.5 dm^3). The applied flow rate of the eluent in this apparatus was equal to 8 dm^3/h, while the feed flow rate of the sucrose solution (50% w/v) was equal to 230 cm^3/h.

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
	Not known				

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.)

No demonstration projects on application of RACRs are known.

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
	Not known			

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)

An application of annular chromatographic separation is widely described in the literature, while only a few applications of *RACR*s are reported and discussed. They are listed as follows:

- hydrolysis reaction (hydrolysis of methyl formate) - Cho et al. (1980a, 1980b),
- sucrose inversion – Sarmidi & Barker (1993),
- reversible esterification (production glycerol triacetate) – Lang (2003).

The listed examples indicate a possible area for preparative and industrial applications of *RACR*s in the fine chemical, food and pharmaceutical industries, where high purity products are required and simultaneously other available methods of product separation (purification) are ineffective.

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?
Design and engineering for commercial scale development	*RACR*s have been developed on the laboratory and preparative scale and no designing rules are available for the industrial scale. New concepts are needed for developing the commercial scale, which would also address the	R&D projects carried out at the universities in collaboration with equipment producers.

	issues of energy and material efficiency as well as optimal operating conditions.	
Modelling and scaling-up	Existed mathematical models have to be reviewed and verified to develop a robust, reliable and universal tool to design and optimize the processes carried out in *RACR*s. Also useful, reasonable criteria of RACRs application as well as methodology of process parameters determination should be elaborated.	R&D projects carried out at the universities in collaboration with equipment producers.
Control systems for commercial RACRs	Proper control of the *RACR*s performance (flow rate of eluent, angular velocity of rotation) is crucial for their efficient operation.	R&D projects carried out at the universities in collaboration with equipment producers.

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?**
High specific eluent consumption	Eluent consumption should be minimized by operating RACRs at optimal conditions. Also carrying out of process with several feeding nozzles as well as different types of elution (isocratic, step, gradient) should be considered.	Optimization procedure should be implemented to search for the optimal operating conditions. This challenge should be addressed in the R&D projects on engineering and design concepts for commercial scale RACRs (pos. 1 in Table 4)
Inefficient bed utilization	Process performance with several feeding nozzles should be considered.	Optimization procedure should be implemented to search for the optimal operating conditions for RACRs equipped with several feeding nozzles. This challenge should be addressed in the R&D projects on engineering and design concepts for commercial scale RACRs (pos. 1 in Table 4)
Improvement of products purity (separation efficiency)	Products purity (separation efficiency) strongly depends on the peaks spreading. To control efficiently the peaks spreading an influence of axial dispersion and pore diffusion should be minimized. This is usually done by minimizing the packing particle diameter, which causes in turn an increase of flow resistances and pressure drop in the bed. Particle size uniformity and packing quality are also essential to keep a contribution of the axial dispersion as small as possible.	Optimization procedure should be implemented to search for the optimal values of particle diameter and eluent flow rate. This challenge should be addressed in the R&D projects on engineering and design concepts for commercial scale RACRs (pos. 1 in Table 4)

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 6)

Publications listed below concern the reactive chromatography and they are cited in this report. Papers dedicated directly to the reactive chromatography process carried out in the rotating annular chromatographic reactors are marked as "*RACR*" in the **Remarks** column of Table 6.

A several representative papers dedicated to the chromatographic separation carried out in the rotating annular chromatographs are also listed and marked as "RAC" in this column.

Table 6. Key publications on the technology

Publication	Publication type (research paper/review/book/ report)	Remarks
D.C.S. Azevedo, A.E. Rodrigues, 2001, Design methodology and operation of a simulated moving bed reactor for the inversion of sucrose and glucose-fructose separation, *Chemical Engineering Journal,* 82, 95-107.	Research paper	
M. Bechtold, S. Makart, M. Heinemann, S. Panke, 2006, Integrated operation of continuous chromatography and biotransformations for generic high yield production of fine chemicals, *Journal of Biotechnology,* 124, 146-162.	Review paper	
M.C. Bjorklund, R.W. Carr, 2002, Enhanced methanol yields from the direct partial oxidation of methane in a simulated countercurrent moving bed chromatographic reactor, *Industrial and Engineering Chemistry Res*earch, 41, 6528-6536.	Research paper	
G.F. Bloomingburg, G. Carta, 1994, Separation of protein mixtures by continuous annular chromatography, *The Chemical Engineering Journal*, B19-B27.	Research paper	RAC
E.A. Borges da Silva, A.A. U. De Suoza, S. G. U. De Suoza, 2005, Simulated moving bed technology in the reactive process of glucose isomerization, *Adsorption*, 11, 847-851.	Research paper	
E.A. Borges da Silva, A.A. U. De Suoza, S. G. U. De Suoza, A.E. Rodrigues, 2006, Analysis of the high-fructose syrup production using reactive SMB technology, *Chemical Engineering J*ournal, 118, 167-181.	Research paper	
J. Brozio, H.J. Bart, 2004, A rigorous model for annular chromatography, Chemical Engineering and Technology, 27, 962-970.	Research paper	RAC
R.W. Carr, 1993, Continuous reaction chromatography, pp. 421-447 in G. Ganetsos, P. Barker (Eds.), *Preparative and production scale chromatography*, Marcel Dekker, New York.	Research paper	RACR
K. B. Cho, R.W. Carr, R. Aris, 1980a, A continuous chromatographic reactor, *Chemical Engineering Sci*ence, 35, 74-81.	Research paper	RACR
K. B. Cho, R.W. Carr, R. Aris, 1980b, A new	Research paper	RACR

continuous flow reactor for simultaneous reaction and separation, *Separation Science and Technology,* 15, 679-696.		
J. Coca, G. Adrio, C.Y. Jeng, S.H. Langer, 1993, Gas and liquid chromatographic reactors, pp.449-475 in G. Ganetsos, P. Barker (Eds.), *Preparative and production scale chromatography*, Marcel Dekker, New York.	Book	
T. Falk, A. Seidel-Morgenstern, 1999, Comparison between a fixed-bed reactor and a chromatographic reactor, *Chemical Engineering Sci*ence, 54, 1479-1485.	Research paper	
G. Ganetsos, P. Barker, J. Ajongwen, 1993, Batch and continuous chromatographic systems as combined bioreactor-separators, pp. 375-394 in G. Ganetsos, P. Barker (Eds.), *Preparative and production scale chromatography*, Marcel Dekker, New York.	Book	
D. Gelosa, M. Ramaioli, G. Valente, M. Morbidelli, 2003, Chromatographic reactors: esterification of glycerol with acetic acid using acidic polymeric resins, *Industrial and Engineering Chemistry Research,* 42, 6536-6544.	Research paper	
S. Goto, Y. Takahashi, 1993, Continuous rotating annular chromatography, pp.127-142, in G. Ganetsos, P. Barker (Eds.), *Preparative and production scale chromatography*, Marcel Dekker, New York.	Book	
K. Hashimoto, S. Adachi, H. Noujima, Y. Ueda, 1983, A new process combining adsorption and enzyme reaction for producing higher fructose syrup, *Biotechnology and Bioengineering*, 25, 2371-2993.	Research paper	
F. Hilbrig, R. Freitag, 2003, Continuous annular chromatography, *Journal of Chromatography B*, 790, 1-15.	Review	RAC
A. J. Howard, G. Carta, C.H. Byers, 1988, Separation of sugars by continuous annular chromatography, *Industrial and Engineering Chemistry Research,* 27, 1873-1882.	Research paper	RAC
M. Kawase, T.B. Suzuki, K. Inoue, K. Yoshimoto, K. Hashimoto, 1996, Increased esterification conversion by application of the simulated moving-bed reactor, *Chemical Engineering Science*, 51, 2971-2976.	Research paper	
F. Lang, 2003, *A continuous annular chromatographic reactor*, Ph.D. Thesis, Swiss Federal Institute of Technology (ETHZ), Zurich.	Ph.D. Thesis	RACR
F. Lode, M. Houmard, C. Migliorini, M. Mazzotti, M. Morbidelli, 2001, Continuous reactive chromatography, *Chemical Engineering Sci*ence, 56, 269-291.	Research paper	RACR
M. Maurer, U. Altenhoner, J. Strube, A. Untiedt, H. Schmidt-Traub, 1996, Dynamic simulation of a simulated moving-bed chromatographic reactor for the inversion of sucrose, *Starch*, 48, 452-457.	Research paper	
M. Mazzotti, A. Kruglov, B. Neri, D. Gelosa, M. Morbidelli, 1996, A continuous chromatographic reactor: SMBR, *Chemical Engineering. Sci*ence, 51, 1827-1836.	Research paper	
M. Mazzotti, B. Neri, D. Gelosa, M. Morbidelli,	Research paper	

1997, Dynamics of chromatographic reactor: esterification catalysed by acidic resins, *Industrial and Engineering Chemistry Research,* 36, 3163-3172.		
J.M. Meissner, G. Carta, 2002, Continuous regioselective enzymatic esterificationin a simulated moving bed reactor, *Industrial and Engineering Chemistry Res*earch, 41, 4722-4732.	Research paper	
M. Minceva, A.E. Rodrigues, 2005, Simulated moving-bed reactor; reactive separation regions, *AIChE Journal,* 51, 2737-2751.	Research paper	
A.K. Ray, R.W. Carr, 1995, Experimental study of a laboratory-scale simulated countercurrent moving bed chromatographic reactor, *Chemical Engineering Science,* 50, 2195-2202.	Research paper	
K. Reissner, A. prior, J. Wolfgang, H.J. Bart, C.H. Byers, 1997, Preparative desalting of bovine serum albumin by continuous annular chromatography, Journal of chromatography A, 763, 49-56.	Research paper	RAC
M. Sardine, D. Schweich, J. Villermaux, 1993, Preparative fixed-bed chromatographic reactor, pp. 477-522 in G. Ganetsos, P. Barker (Eds.), *Preparative and production scale chromatography*, Marcel Dekker, New York.	Book	
M.R. Sarmidi, P.E. Barker, 1993, Simultaneous biochemical reaction and separation in a rotating annular chromatograph, *Chemical Engineering Sci*ence, 48, 2615-2623.	Research paper	RACR
C.D. Scott, R.D. Spence W. G. Sisson, 1976, Pressurized annular chromatograph for continuous separations, Journal of Chromatography, 126, 381-400.	Research paper	RAC
M.T. Shieh, P.E. Barker, 1996, Combined bioreaction and separation in a simulated countercurrent chromatographic bioreactor-separator for hydrolysis of lactose, *Journal of Chemical Technology and Biotechnol*ogy, 66, 265-278.	Research paper	
V.M.T.M. Silva, A.E. Rodrigues, 2005, Novel process for diethylacetal synthesis, *AIChE Journal*, 51, 2752- 2768.	Research paper	
A. Stankiewicz, 2003, Reactive separation for process intensification: an industrial perspective, *Chemical Engineering and Processing*, 42, 137-144.	Review	
G. Strohlein, M. Mazzotti, M. Morbidelli, 2005, Simulated Moving-Bed Reactors, pp. 183-201 in K. Sundmacher, A. Kienle, A. Seidel-Morgenstern, (Eds.), *Integrated Chemical Processes – Synthesis, Operation, Analysis and Control*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.	Book	RACR
G. Strohlein, F. Lode, M. Mazzotti, M. Morbidelli, 2004, Design of stationary phase properties for optimal performance of reactive simulated-moving-bed chromatography, *Chemical Engineering Sci*ence, 59, 4951-4956.	Research paper	
A.L. Tonkovich, R. Carr, R. Aris, 1994, A simulated countercurrent moving bed chromatographic reactor for the oxidative	Research paper	

coupling of methane: experimental results, *Chemical Engineering Science.,* 49, 4647-4656.		
A. Toumi, S. Engell, 2004, Optimization-based control of a reactive simulated moving bed process for glucose isomerization, *Chemical Engineering Science,* 59, 3777-3792.	Research paper	
A. Uretschläger, A. Jungbauer, 2002, Preparative continuous annular chromatography (P-CAC), a review, *Bioprocess and Biosystem Engineering,* 25, 129-140.	review	RAC
A. Uretschläger, A. Jungbauer, 2000, Scale-down of continuous protein purification by annular chromatography. Design parameters for the smallest unit, Journal of Chromatography A, 890, 53-59.	Research paper	RAC
R.G. Wetherold, E.H. Wissler, K.B. Bischoff, 1974, An experimental and computational study of the hydrolysis of methyl formate in a chromatographic reactor, pp. 181-190 in H.M. Hulburt (Ed.), *Advances in Chemistry*, Series 133, Am. Chem. Soc., Washington D.C.	Book	
W.Yu, K. Hidajat, A.K. Ray, 2003, Modelling, simulation and experimental study of a simulated moving bed reactor for the synthesis of methyl acetate ester, *Industrial and Engineering Chemistry Research,* 42, 6743-6754.	Research paper	
Y. Zhang, K. Hidajat, A.K. Ray, 2004, Optimal design and operation of SMB bioreactor: production of high fructose syrup by isomerization of glucose, *Biochemical Engineering J*ournal, 21, 111-112.	Research paper	
Z. Zhang, K. Hidajat, A.K. Ray, 2001, Application of simulated countercurrent moving-bed chromatographic reactor for MTBE synthesis, *Industrial and Engineering Chemistry Research,* 40, 5305-5316.	Research paper	
Z. Zhang, K. Hidajat, A.K. Ray, 2002, Multiobjective optimization of simulated countercourent moving bed chromatographic reactor (SCMCR) for MTBE synthesis, *Industrial and Engineering Chemistry Research,* 41, 3213-3232.	Research paper	

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.)

no patents have been found

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent

4.3 Institutes/companies working on the technology

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

No institutes or companies are known working on development of industrial and commercial *RACR*s, however PRIOR Engineering Group claims a manufacturing of Production Scale Unit for the annular reactive chromatography.

In Table 8 a several research groups carrying out research on application of RACRs and/or RAC are listed.

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
Laboratorium fur Technishe Chemie, ETH Zurich	Switzerland	Team leaders - M.Morbidelli, M. Mazzotti
Oak Ridge national Laboratory, Oak Ridge, Tenn.	USA	Team leader - C.D. Scott
Department of Chemical Engineering, University of Virginia, Charlottesville, Virginia	USA	Team leader – G. Carta
Department of Chemical engineering, University of Aston, Birmingham	UK	Team leader – P.E. Barker
Department of chemical engineering and Material science, university of Minnesota, Mineapolis, Minnesota	USA	Team leaders - R.W. Carr jr., R. Aris

5. Stakeholders

5.1 Suppliers and developers

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

No suppliers of commercial-scale *RACR*s are known, however a few developers of laboratory or preparative *RACR*s are listed in Table 9, including PRIOR Engineering Group, which claims a manufacturing of Production Scale Unit for the annular reactive chromatography.

The most *RACR*s employed in a laboratory or preparative practice has been built by researchers, just following the original constructions.

Table 9. Supplier and developers

Institute/Company	Country	Remarks
Oak Ridge National Laboratory (ORNL)	USA	Gas pressurized RAC, constructed in 1976 with later improvements
PRIOR Separation Technology GmbH, Götzis,	Austria	RAC now commercially available (commercial name: Preparative Continuous Annular Chromatograph P-CAC). P-CACs can be directly used as RACRs

Prior Engineering Group AG, Zurich http://www.prioreng.com/	Switzerland	Downstream Processing via Preparative Continuous Annular Chromatography (commercial name P-CAC): * Lab Scale Units (LabP-CAC) * Pilot Scale Units * Production Scale Units (iP-CAC) * CAP3 (Continuous Accelerated Pure Protein Production) P-CACs can be directly used as RACRs

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 fine chemical, pharmaceutical and food industry. RACRs can be also successfully applied in production of materials of special properties (e.g. to separate enatiomers etc.).

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

Rotating Annular Chromatographic Reactors (RACRs) can be a promising technology for niche applications in the fine chemical, pharmaceutical and food industries, in small-to medium scale processes. With application of this technology a high quality (high purity) products of special properties can be obtained, while integration of reaction and chromatographic separation in one apparatus helps to increase the yield and selectivity, particularly for reversible reactions. RACRs can be an attractive alternative for simulated moving bed chromatographic reactors (SMBCRs), when multiple reactions or reacting systems with more then two products are involved. The technology remains on a middle stage of development and no industrial applications are known, however a several processes carried out in the laboratory and preparative scale have been successfully investigated.