EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Structured reactors (structures in arrays and arranged beds of conventional catalyst particles)

TECHNOLOGY CODE: 1.2.1.4

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1. Technology

1.1 Description of technology / working principle

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

Conventional catalytic fixed-bed reactors for carrying out heterogeneous processes contain catalyst particles of more or less uniform size in a reaction zone. An inherent feature of such reactors is their random and structural maldistributions that influence negatively yield and selectivity of the process. Pressure drop in such beds is rather high whereby the smaller catalyst particles, the higher pressure drop becomes. Structured reactors of relatively high void fraction contain a catalyst that is placed in an ordered way in a reaction zone thereby eliminating the above drawbacks of conventional packed-bed reactors.
Monolithic reactors are the most commonly used structured reactors. Such reactors contain a catalyst in a form of continuous unitary structures with small, parallel, straight passages. The catalytically active material is present on or inside the walls of these passages. Monoliths are made usually from ceramics, but metals are also used. No matter what material is used to manufacture the monolithic structure, such structured reactors are operated nearly adiabatically. Thus, they are not suitable for carrying out processes that require heat exchange with the surroundings from the reaction zone on site. Monoliths are, however, the dominant structures in environmental applications where adiabatic operation does not make harm neither to the catalyst/reactor nor to the process. The monolithic catalysts dominate among the catalysts for car emissions. Monolithic reactors/catalysts are a subject of Technology Report No. 1.2.1.2. All the other structured reactors and catalysts are a subject of this report. To distinguish the catalysts in these reactors from the monolithic catalysts with straight channels they will be named the structured, arrayed catalysts. Two following categories of arrayed structured catalysts can be distinguished: (i) **Arrays of Structural Elements (ASE)** that are similar to or identical with monolithic structures but containing twisty (zig-zag) passages and/or interconnected passages, structural packing of distillation columns, intensive heat exchangers and static mixers, and (ii) **Arrays of Conventional Catalyst Particles (ACCP)** with packets of catalyst particles that are located in the reaction zone in a predetermined way.

(i) The **ASE**s are the arrays of structural elements allowing and/or forcing the twisty flow of reactants with a significant component that is perpendicular to the dominant direction of flow of reactants through the reaction zone. The surface is typically covered with a layer of transition metal oxides and then catalytic species are incorporated into that layer. These elements are covered with a catalytic species directly or in a layer that is deposited on the element surface if catalytic species may not be deposited on the surface directly. Methods for deposition of catalytic species on non-catalytic surface are presented in review papers of Xu Xiaoding and Moulijn (1998, 2006), and Maillle (2006). Arrays of fibers (woven and knitted structures) belong also to this category of structured catalysts (arrays of wires, grids, and gauzes are described in Technology Report No. 1.2.1.3). The ASEs are characterized with low pressure drop, from 10 to 100 times lower than that for conventional packed beds.

(ii) The **ACCP**s are located in a reaction zone in an ordered way. Particles are placed between elements and the gas contacts particles via diffusion or flow through. Sandwich structures dominate in this category of structured reactors. Parallel-passage reactors (PPR), lateral-flow reactors (LFR), and bead-string reactors (B-SR) belong also to this class of reactors. Technologies for the manufacture of conventional particulate catalysts as well as for the elements containing the particles are usually well known. The manufacture of granular catalysts is well known to those skilled-in-the art. Pressure drop in sandwich structures is slightly lower, while in PPR, LFR, and B-SR is significantly lower (1 to 2 orders of magnitude) than that in packed beds.

1.2 Types and "versions"

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

1.2.1. Arrays of structural elements (**ASE**)
1.2.1.1. Monoliths with Twisty passages and/or Interconnected Passages (**MTIP**)
Conventional monoliths contain parallel channels. In the MTIPs passages are twisty (e.g. zig-zag) and/or passages are interconnected. The MTIPs are made usually from metal although ceramic MTIP are also in use. The metal MTIPs are usually made from Fecralloy®, Kanthal® or stainless steel that are appropriately washcoated (usually with alumina) and covered by catalytic species. The metal MTIP consist of alternate layers of crimped and flat strips, possible perforated. When arranged together they form twisty passages that are interconnected when manufactured from perforated plates. Exemplary methods to arrange the twisty flow through the or to form the possibility of exchange between neighboring passages are illustrated by metal structures that were designed by EMITEC for car catalysts (Held et al., 1994; Brück et al., 1994), see Figs 1-3.

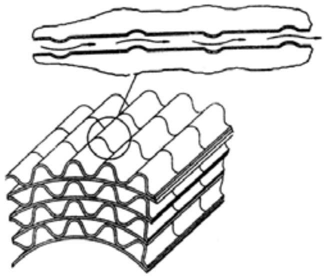


Fig. 1. EMITEC structure type TS

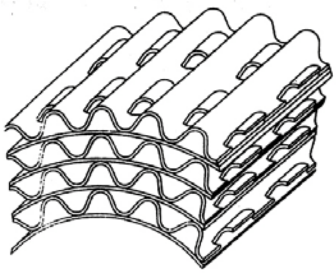


Fig. 2. EMITEC structure type SM

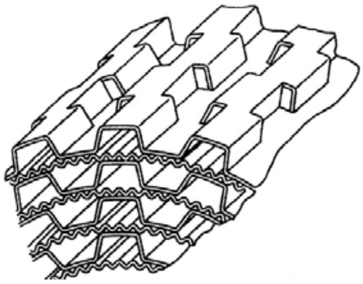
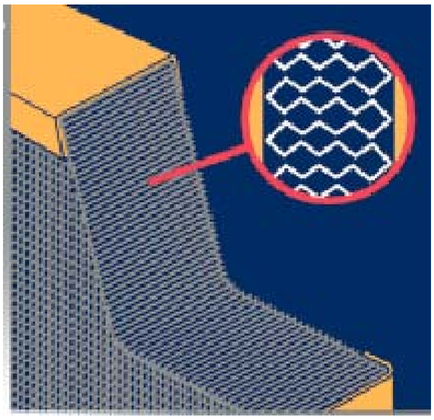


Fig. 3. EMITEC structure type TS

The interconnecting holes improve mixing and lateral heat transfer in the structure and provide the possibility of the whole of the catalytic surface being used, even if flow distribution at the catalyst front is not uniform. Heat transfer in direction perpendicular to flow in enhanced via conduction through metal walls of the channels (Cybulski and Moulijn, 1994). Appropriate modifications of such structures can be used for the other applications. One of them is that developed by ABB Lummus Global. Its structured packing comprises sheet material formed into vertical preferably square channels containing vortex generators formed from the sheet material. The channels, while vertically linear, are periodically interrupted by the vortex generators providing tortuous fluid paths along the channels. The thus formed vortex generators form openings between adjacent channels providing fluid communication between and uniform flow within the different channels.



The BASF catalyst of this type that is used for oxidation of hydrocarbons and CO (based upon Camet design, herringbone support made from a very thin metal foil) is shown in Fig. 4. The MTIP reactors are widely used for environmental processes (deNOxification, SCR, incineration of VOC). Other applications of MTIPs have been studied but none appear to have reached a significant large-scale commercialization.

Fig. 4. BASF Camet catalyst for oxidation of hydrocarbons

1.2.1.2. Open cross-flow structures (**OCFS**)

The OCFSs consist of inserts of different shape and size that are regularly placed in a pipe, typically of circular or rectangular cross section. Elements inserted into the tube are inclined to the axis, usually by less than 45^0. The very basic structure developed by Sulzer CHEMTECH that can be considered to be a pioneer in such structures for reactors contains superimposed individual corrugated sheets with the corrugations in opposed orientation such that the resulting unit is characterized by an open cross-flow structure pattern. The angle of channels to the axis of flow is in principle variable between 0 and 90^0 whereby the optimum value lies between 30 and 45^0. Consecutive elements (along the reactor axis) are installed rotated through 90^0 on the axis (Fig. 5). Inserts of this or another shape provoke the main stream of fluid(s) to be divided into a number of sub-streams that are recombined, intensifying the turbulence of the current and heat transfer within the structure and between the fluid and the reactor wall. There is a large number of OCFSs, which differ from each other with shape and size of inserts. Sulzer, that can be considered as a pioneer in this field, offers several types of OCFSs designed as SMX, SMXL, SMXS, SMV, SMF, and SMR that are used, first of all, as static mixers. The geometric surface area of the OCFSs ranges from 300 to 1800 m^2/m^3, void fraction is ca. 90 %. The OCFSs are made from metal (washcoated and covered by catalytic species) or ceramics (Fig. 6) that do not need washcoating to transform it into the catalyst. The structure is characterized by a good macro-level mixing, intensive radial mixing, narrow RTD, improved mass and heat transfer between fluid and solid, in a cross section (effective thermal conductivity of the structure can be up to two times greater than that for conventional particulate bed), and between the bed and the wall. Pressure drop in OCFSs is 10-100 lower than in fixed beds of conventional catalysts. Many static mixers have a structure of OCFE. As such those static mixers can be considered a good basis for structured catalysts of OCFE type. More information on static mixers can be found in Technology Report No. 1.1.4. The OCFSs can be suitable for carrying out strongly exothermic reactions such as selective oxidations.

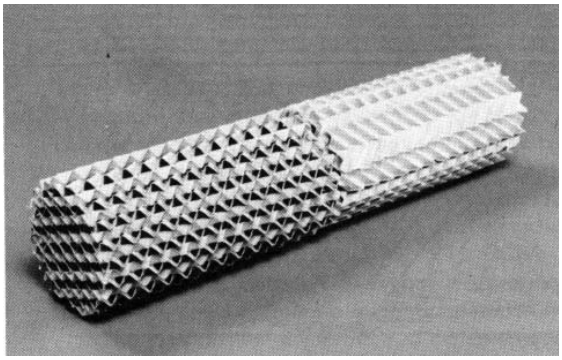


Fig. 5. The Sulzer OCFS metal structure

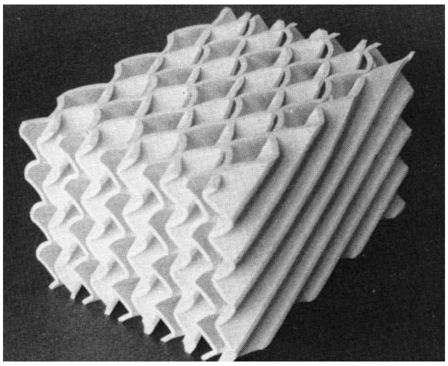


Fig. 6. The Sulzer OCFS ceramic structure

1.2.1.3. Plate-type catalysts (**PTC**)

Fig. 7. Plate-type catalyst (Hitachi)

The PTCs are in fact a subclass of the OCFSs. They consists of metal (stainless steel or aluminum) sheets, metal net or perforated metal plates with the catalytic species deposited onto, and assembled in modules that are inserted into tubes of multitubular reactor or in the reactor itself in layers (Fig. 7). The PTC: (i) are less prone than monoliths to blockage owing to their structure, which permits slight vibration of the individual plates, (ii) the metal support makes the plates more resistant to erosion than the all-ceramic materials, (iii) the plates are very thin, so only a small portion of the cross section is obstructed and pressure drop is very low. Typical data for the industrial PTC (Hitachi Zosen product information, 1990) are as follows: element size: 500x500 mm, length: 500-600 mm; wall thickness: 1.2-0.8 mm; pith: 6.9-3.8 mm; geometric surface area: 285-500 m^2/m^3; void fraction: 0.82-0.8. Plates are coated with a layer of the catalyst (SCR reported by Kotter et al., 1992). Babcock Hitachi has developed also a plate-like structure covered with fabric of inorganic fibers. To maintain a high deNOxification efficiency a plate type catalyst is prepared by applying catalyst components on a substrate fabric of inorganic fibers like glass fibers to improve the plate strength without thickening the plate. Kawasaki Heavy Ind. Ltd. worked out a plate catalyst and patented an integrated catalyst unit comprising a plurality of spaced foamed metallic plates, each having a mixture of TiO_2 carrier and a catalytic substance supported thereon, said plates. Void fraction of the structure ranges between 70 % to 90 % and plates are 1 mm to 5 mm thick before catalytic substance addition. Allied Signal Inc. has worked out a catalytic converter comprising a metal plate fin elements defining a large plurality of fins arranged in an axial succession of offset fin rows. The elements are shifted to each other by a half of fin to divide substreams of a fluid. The converter is claimed to be appropriate for the decomposition of ozone and the oxidation of atmospheric pollutants. Nippon Steel Corp. has developed a catalyst structured support consisting of plain plates and a corrugated plates, both being made of nonwoven fabric of metal fiber, alternately superposed over each other and rolled or laminated. Recently, a microstructured plate reactor and microstructured reactor/heat exchanger assembled from aluminum plates appropriately grooved was developed (Rebrov et al., 2001). It provided nearly isothermal operation (less than 6 ^{0}C peak for an adiabatic temperature rise of about 1400 ^{0}C) of ammonia oxidation process. Plate-type catalysts are extensively studied by scientists from Politecnico da Milano.

1.2.1.4. Catalysts for strongly exothermic reactions (**CER**)

A search for metal structures that would exhibit good flow and heat transfer characteristics has brought the Institute of Chemical Engineering, Gliwice, Poland to a combination of elements as shown in Fig. 8. Radial mixing of the reactants is quite intense contributing significantly to heat transfer from the reaction zone and the coolant. The heat exchange is enhanced by heat conduction in the elements that are made from metal. Overall heat transfer coefficients between fluid flowing through the structure and the tube wall (depending on the configuration of the structured carrier) are similar to that for randomly packed ceramic rings over a large range of Re-numbers, while pressure drop is much lower than in packed beds. Heat transfer characteristics for the best configuration studied was nearly two times better than that for ceramic rings. This structured catalyst was successfully tested in *n*-butane oxidation to maleic anhydride.

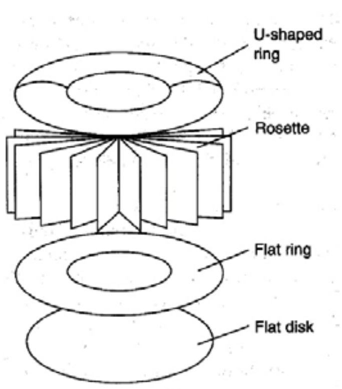


Fig. 8. Elements of the structured catalyst of high thermal characteristics

Scientists from Politecnico di Milano and EVC Tech. AG (Switzerland) worked out a catalyst support for selective gas phase reactions in a tubular fixed bed reactor comprising a metallic monolith having channels the walls of which are adapted to receive a catalytically active phase or an intermediate layer acting as a carrier for a catalytically active phase. The monoliths are coated with catalytically active material and loaded lengthwise into tubular reactors, the channels being parallel to the length of the reactors. The catalysts are particularly useful in the chlorination/oxychlorination of alkenes and alkanes, and the oxidation of alkenes. Compared with the use of conventional pelleted catalysts or in the form of ceramic monoliths the catalyst discussed offers greater yields and selectivity, the avoidance of hot spots, greater catalyst life and flexibility in use. Corning that is a world leader in ceramic structured supports, developed also metallic (copper) supports of improved thermal characteristics with straight channels, zig-zag channels and wall-flow channels. Some metal structures can be produced by extrusion. A reactor comprising a catalyst based upon metallic support contains heat conductive tubes with the catalyst inside whereby the gap distance between the reactor tubes and the monolithic catalyst or catalyst support structure does not exceed about 250 μm. Catacel Corp. proposes filling tubes of a tubular reactor with special cartridges. The cartridges are composed of a plurality of spaced-apart elements that are formed from flat and corrugated metal strips (made of solid or screen material) that are spirally wound around the internal tube. The corrugations are skewed, such that the cartridges impart a swirl to gases flowing through the tube. The corrugations of the strips in adjacent cartridges are oriented differently, so that successive elements impart different swirls to the gases. This promotes mixing of gases and heat transfer between elements and the outer tube, which contain elements. The cartridges can be inserted and removed from tubes using a special device.

1.2.1.5. Fibrous structured catalysts (**FSC**)

Fibrous structured catalysts are the structures of threads that are ordered by knitting or weaving and structures of fibers that are formed by chemical or mechanical processing of ceramic or metal sheets. Catalytic species such as noble metal catalysts (Pd, Pt, and Ru) and zeolites are deposited on or incorporated in the fibers. Methods of deposition and/or incorporation of the catalytic metal into the fibers are similar to these for the other catalyst supports and are known to those skilled in the art. Zeolitic (ZSM-type) crystals were grown using know methods whereby zeolites were deposited on ceramics only to avoid dilatations with metal fibers. Before deposition, the fiber structure must be degreased and cleaned, and sometimes treated specifically to increase of specific surface area or adhesion of catalytic species to the fiber surface (e.g., with hot acids in the case of carbon fibers, washcoating in the case of metal or glass fibers).

The catalysts based upon glass fibers (GFC) or carbon fibers (CFC) are usually knitted or woven fabrics (see Fig. 9). Threads (ca. 0.5-1 mm in dia.) of the fabric consist of a bundle of elementary filaments that are spun to the size of 1-15 μm and rolled up before being packed into a tubular reactor. Structures of sintered metal (SMC) (made of Inconel or FeCrAlloy) or carbon fibers are deposited on a permeable support. In a form of slices the structures are placed in a reactor (tubular or a column) perpendicularly to flow of reactants (Fig. 10).

Topsøe worked out a catalyst having high catalytic selectivity for the oxidation of ammonia to nitrogen oxides, with the active catalytic components supported on a structured carrier of a heat resistant material consisting of silicate fibers with an average fiber diameter of 2-50 μm and an average fiber length of 2-60 mm. This company developed also a catalyst for preparing aldehydes on a carrier consisting of silica rich fibers. Any FSC can be appropriately located in a stirred tank reactor. Carbon fibers that are formed on a support surface in course of passing hydrocarbon(s) with hydrogen and nitrogen at elevated temperatures occur in two forms: nanofibers or nanotubes. Fe and Co in the support can provide carbon nanotubes while Ni leads to nanofibers.

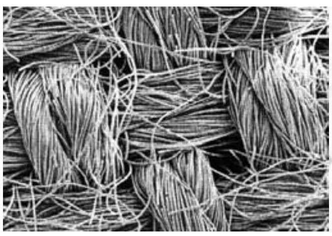


Fig. 9. Woven active carbon fiber catalyst

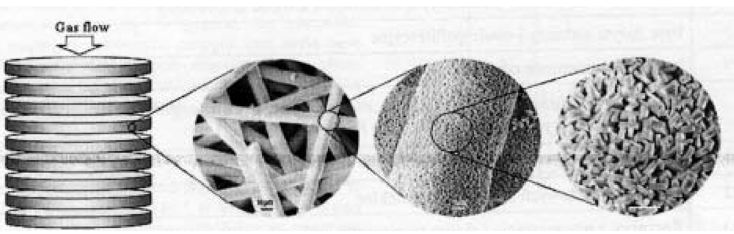


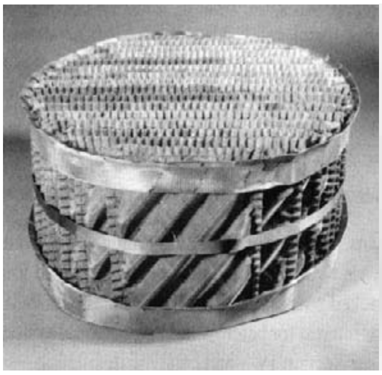
Fig. 10. Fibrous sintered metal structured catalyst arranged in layers

Full physical characterization and comparison with conventional catalysts was the aim of many studies with no tests of catalytic activity. The FSCs have large surface area and great catalytic activity. Due to a small size of elements of the structure diffusion limitations are usually avoided.

1.2.2. Arrays of Conventional Catalyst Particles **(ACCP)**

1.2.2.1. Sandwich structures (**SS**)

Sandwich structures are formed embedding catalyst particles between two (permeable) screens (perforated plates, web of micro-fibers, gauze). Sandwiches are then stacked. Examples of such structures are shown in Figs. 11 and 12 (structures developed by Sulzer) and Fig. 13 (a structure developed by Montz). These structures are particularly suitable for three-phase heterogeneous reactions that are carried out in trickle-beds and bubble columns, particularly as continuously operated loop systems.



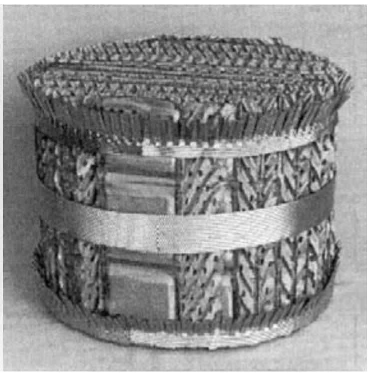
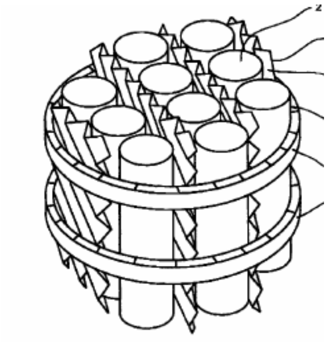


Fig. 11. Katapak® structure Fig. 12. Mellapak® structure Fig. 13. Multipak® structure

Katapak structures developed by Sulzer consist of two pieces of rectangular crimped wire gauzes sealed around the edge, thereby forming a pocket of the order of 10-50 mm wide between the two screens. These catalyst "sandwiches" or "wafers" are then bound together. The modules are arranged into a cubical collection or round collection. A similar structure was developed by BASF AG. A fixed-bed reactor for carrying out reactions in the presence of a particulate heterogeneous catalyst has a structured packing which forms interstices in the reactor interior, in which the quotient of the hydraulic diameter for the fluid flow through the structured packing and the equivalent diameter of the catalyst particles is in the range from 2 to 20, preferably in the range from 5 to 10, to such an extent that the catalyst particles are introduced into the interstices, loosely distributed and discharged under the action of gravity.



BASF AG has also developed a packing that has catalyst-holding and catalyst-free zones. The catalyst-holding zones are formed by hollow cylinders, open at the top and closed at the bottom, aligned along the column vertical axis. The cylinder walls are permeable to the reaction mixture, and impermeable to the catalyst. Structured separation layers (made from corrugated sheets) are in the catalyst-free zones, and the packing is held together by edge deflectors. The packing is shown in Fig. 14.

Fig. 14. BASF structured packing

Sandwich structures found application in syntheses of esters (low acetates) that are carried out with simultaneous distillation (reactive packings).

1.2.2.2 Parallel passage reactor (**PPR**)

In the PPR (see Fig. 15) the catalyst particles are confined in envelopes (modules), between the gauze screens, plate or corrugated, that divide the reaction zone into a number of catalyst layers with empty passages in between. All the gas passages connect the inlet directly with the outlet of the reactor being open at both ends. The gas flows along the catalyst layers penetrating the layers mainly by diffusion. The modules can be assembled in a reaction zone in any configuration. For instance, the envelopes can be of the forms of annuli that are inserted into a column reactor. Pressure drop for the flow through straight passages (ca. 10 mm wide) is much lower than over a packed-bed reactor. The PPR found application in flue gas desulfurization and deNOxification.

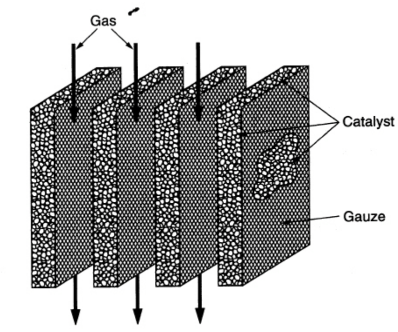
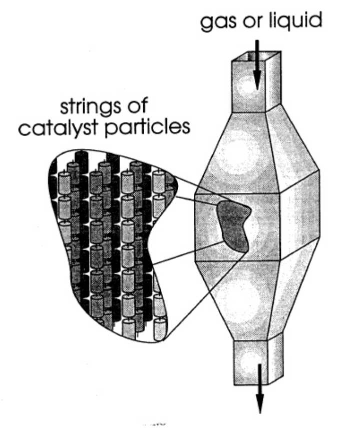


Fig. 15. Parallel-passage reactor

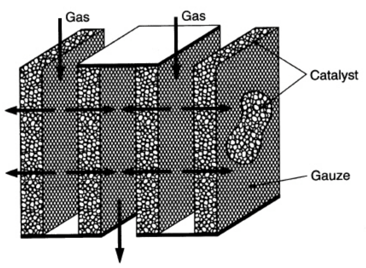
1.2.2.3. Bead-string reactor (**B-SR**)



The B-SR (see Fig. 16) represents the limit of the PPR. The B-SR contains single-catalyst-particle subunits. Conventional particulate catalyst is fixed on parallel strings that are arranged parallel (or cross) to the main flow of reactants. The B-SRs have the advantages of the LFRs without the disadvantages of the LFRs (low mass transfer rates). Monolith with channels that are packed with the catalyst particles are in fact a kind of the B-SR (Strangio et al., 1999).

Fig. 16. Bead-string reactor

1.2.2.4. Lateral flow reactor (**LFR**)



The gas passages in the LFR (Fig. 17) are each closed off at one end, neighboring passages being open and closed off at different ends. Thus, the gas is forced to flow through the layers of catalyst particles. The LFR found application in flue gas cleaning.

Fig. 17. Lateral-flow reactor

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
Increased reactor capability, yields and selectivities of processes. Better product quality	Up to 10 % increase can be expected	There are structural particles and flow maldistributions in conventional packed-bed reactors. This results in (i) non-uniform residence time distribution (RTD) with a. tendency to flow near the reactor walls where catalyst particles are packed more loosely (ii) non-uniform access of reactants to the catalytic surface, worsening the overall process performance, and (iii) unexpected hot spots and thermal runaways of exothermic reactions (mainly in three-phase reactions). The first two factors affect yields and selectivities whereby the size of the outcome depends on the reactor sensitivity to residence time and on the regime the reaction occurs at. The latter one influences safety of the process. Uniform distribution of catalytic species and reactants flow in structured reactors eliminates maldistributions that occur in packed beds thereby leveling the RTD and improving access of reactants to the catalytic surface. Accordingly, all the reactants face the optimal course of reaction conditions. This results in the increase of yield, selectivity and, consequently, reactor capability
Increased safety	No thermal runaways in structured reactors have been reported in the open literature	See above, point (iii). Elimination of flow maldistribution results in the lack of conditions, in which thermal runaway occurs.
Energy savings	Up to 80 % for energy that is required for pumping reactants through the reactor (compared with packed bed reactors)	Pressure drop in most of structured reactors is up to one order of magnitude higher than for empty tubes and 10 to 100 times lower than that in packed beds (it is higher for sandwich structures and the LFR). Accordingly, less energy is required to force reactants flow through the reactor.
Fouling prevention	Savings of 5-10 % in capital costs of plants for cleaning flue gases	Sensitivity of structured reactors to dust in the gas treated is small. Therefore, there is usually no need to install special equipment to entrap dust from gases before entering the structured reactor. Due to a high void fraction of structured reactors and relatively large cross section of passages dust particles are deposited on surfaces of structured catalysts only to minor extent. Therefore both blocking of catalytic surfaces and clogging of the reaction zone is avoided. A larger proportion of dust is deposited on the catalyst particles in sandwich structures and LFRs since the gas flows in those reactors through beds of densely packed particles. However, the proper design of the catalyst and the modules can result in the minimization of dust entrapping: At certain conditions only 10 % of dust particles are entrapped in the beds. Fouling of the modules by dust particles in PPR, B-SR, and LFR does not affect pressure drop in those reactors. This can only block partially surface area of the catalyst. A gentle swinging movements of the strings in the S-BR that is induced by the gas flow, when the strings are connected only at the top end and not at the bottom end

		of the reactor, might be sufficient to remove dust particles from the catalyst if they deposited during the reactor operation.
Efficient way of supplying energy for endothermic reactions	No industrial data available	There is a possibility to supply heat in the B-SR directly to the catalyst by using strings onto which the catalytic material is fixed as electrical heating elements
High “thermal conductivity” of structures compared to typical monolithic catalysts	No economic data available	Effective thermal conductivity of Sulzer structures is up to two times higher than that for typical ceramic random particulate packings. Overall heat transfer coefficient for rosette structures is up to two times higher than for ceramic particles.
Cost savings	No economic data available for proprietary reasons	Low pressure drop in structured catalyst, easy cleaning of the catalyst from dust particles deposited on, low cost of plate-like catalysts and smaller reaction zone (compared to conventional reactors) for some structured catalysts reduce size of plants for cleaning off-gases and, accordingly, their capital costs.
Less emissions to atmosphere	Emission standards by using structured catalysts are reached at lower costs compared to traditional techniques (packed-bed reactors). No industrial data are available but capital and running costs can be substantial (up to 20 %)	Structured reactors are widely used to clean off-gases from NO_x and sulfur compounds (e.g., SCR processes) and to incinerate VOCs CO_2

1.4 Stage of development

ASEs (MTIPs, OFCSs, and PTCs) are well developed although there is a room for further modifications and improvements. A number of industrial applications of MTIPs and PTCs for oxidation of VOCs and reduction of NO_x in off-gases is known. CERs and FSCs are in the very early stage of development. By now, results of fundamental and preliminary attempts of applied research have been reported in the literature. A private information from a person who is involved into the project indicates that a demonstration plant for a catalytic process of high thermal effect is under preparation. At the moment, it is kept, however, in secret.

Some of ACCPs have found industrial applications. SSs such as Katapak-S® and the other sandwich structures are suitable for many catalytic applications such as esterifications, e.g. to methyl acetate, ethyl acetate, and butyl acetate (all of them can be considered as examples of reactive distillation), etherifications, e.g. to MTBE, hydrogenations, e.g. of anthraquinone, or alkylations (Götze et al., 2001). More information about applications of catalytic structured catalysts in reactive distillation can be found in Technology Report No. 2.2.8.1. PPRs and LFRs have found a few industrial applications form cleaning flue gases. Their characteristics show, however, that they will probably not competitive to MTIPs and PTCs. The B-SR is in an early stage of development. Extensive studies on transport phenomena have been performed using model media. However, no application to a particular chemical process has been reported.

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)

Heterogeneous catalytic gas-phase processes are carried out mostly in packed-bed reactors with the bed placed in one or more tubes. Multitubular reactors are typically used for processes with a high thermal effect. Packed bed reactors are characterized by a high pressure drop and structural maldistributions. Reactors with a moving bed of catalyst particles (fluidized bed reactors, risers etc.) are also in a common use. Three-phase reactions are run in a variety of reactor types: stirred tank reactors (possibly with recycle loop) and column reactors (e.g., bubble column reactors, trickle-bed reactors etc.) with packed bed of catalyst particles or moving particles. Conventional reactors are operated nearly adiabatically or heat is supplied to or withdrawn from a reaction zone by heat transfer media, such as water, mineral oils, molten salts or steam.

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)

Structured catalysts and reactors of all types discussed above have found industrial applications. Vast majority of structured catalysts and reactors are used in flue gas cleaning (deNOxification, VOCs incineration etc.) and oxidation of fuels. However, due to proprietary reasons suppliers of the catalysts or plants may not reveal where the catalyst was used, what is capacity of the plant, and for what purpose the catalyst/reactor was used. For instance, Babcock Power Environmental (Babcock-Hitachi is the owner of many patents concerning plate catalysts and reactors that prevail in use for SCR processes) reported that in the US they have over 30,000 MWs of SCRs (for boiler systems) commissioned, in design or evaluation, and under construction. In addition, BP's licensor has over 26,000 MWs of SCRs operating in Europe. Not all SCRs plants are, however, based upon structured catalysts. The German company, E.ON, has owned and operated 44 SCR systems, totaling 12,300 MWs. Therefore, it is impossible to enumerate all applications in this short report. Hereunder, only exemplary applications, mainly for deNOxification and VOC incineration, are shown that have been reported in the literature.

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
Power station	Coal fired boilers in Japan for stations representing a total of 14,300 MW	DeNOxification of flue gases with the use of the Hitachi Zosen system.	30 units		Highly positive results, considering expansion of the technology, no details available
Power station (pulverized coal fired boiler)	Hitachi/AES Sommerste, UK	DeNOxification of flue gases with the use of the Hitachi PTC. Steam sootblower installaed to clean the	Catalyst volume – 897 m^3, gas flow 65000000 lb/hr.	July 1999	Operation better than designed. The catalyst remained clean with no deposit of dust or erosion only ash buildup found on

		catalyst in the course of operation			horizontal surfaces but not on catalyst surface. DeNOxification efficiency 90 %.
Power station (pulverized coal fired boiler)	Hitachi/The Roxboro 4 unit owned by Carolina Power and Light	DeNOxification of flue gases with the use of the Hitachi PTC. Acoustic horns are used for catalyst cleaning.	Catalyst volume – 314 m^3, gas flow 1,735,300 SCFM	July 2001	No plugging has been experienced. DeNOxification efficiency 79 %.
Power station (pulverized coal fired boiler)	Hitachi/The Hawthorn 5 unit owned by Kansas City Power & Light	DeNOxification of flue gases with the use of the Hitachi PTC. Acoustic horns are used for catalyst cleaning.	Catalyst volume – 477 m^3, gas flow 5,595,000 SCFM	May 2001	No increase of pressure drop in the catalyst section was observed.
Power station, deNOxification of flue gas	Kraftanlagen Roto-Cat	SCR, catalytic air-heater, based on Ljungstrőm technology (the PTC reactor)	Dia. 19.5 m; processin g ca. 1.5 million m^3/h.	1987	Successful operation for years.
Oil processing , cleaning off-gases	Yokkaichi refinery of Showa Yokkaichi Sekingu	Flue gas desulsurization (SFGD process) also modified for removal of NO_x. (the PPR)	125,000 Nm^3/h	1973	Successful operation (90 % desulfurization) for several years (Groenendaal et al., 1976)
Oil processing , cleaning off-gases	PPR : Rheinische Olefin Werke at Wesseling, Germany	DeNOxification of flue gases from six ethylene crackers (The PPR)	120 m^3 of the catalyst	April 1990	Probably the first industrial application of structured catalyst for reduction of NO_x emissions (to about 40 ppm (Samson et al., 1990)).
Oil processing , cleaning off-gases	LFR: California refinery	DeNOxification of flue gases from the gas-fired furnace (the LFR)	5000 Nm^3h	1991	The first industrial application of the LFR (Woldhuis et al., 1991; Goudriaan et al., 1991)
Cleaning industria-loff-gases	Ehovoc Oy	VOCs catalytic incineration	Ca. 20 plants, 500-35000 Nm^3/h		Successful operation, references of the users available. Expected life-time of the catalyst is 20-25 years

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.)

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
Petrochemistry	Shell's refinery in Pernis, the Netherlands	Flue gas desulsurization (SFGD process)	1971	Based upon the experience from Pernis (20,000 operating hrs) an industrial plant was designed and built (Dautzenberg et al., 1971)
Organic synthesis	Unknown	An organic process with high thermal effect	Under construction and/or preliminary trials	An information gained from a person who is involved into the project that is secret at the moment

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)

By now, structured catalyst and reactors are used in industries that produce **bulk chemicals**. This is also the predicted trend in the future. The development of applications of structured catalysts/reactors of almost all types for protection of environment can be expected: (i) for air protection (cleaning of flue gases) with modifications of structures relevant to characteristics of streams treated and environmental standards, and (ii) for catalytic wet air oxidation of wastewaters (Cybulski, 2007).

Extensive studies are carried out on structures that could be used for catalytic reactions with high thermal effect. Selective catalytic oxidations of hydrocarbons, e.g., methanol to formaldehyde, *o*-xylene to phthalic anhydride, *n*-butane to maleic anhydride, ethylene to ethylene oxide, oxychlorinations and hydrogenations are among these processes. Search for structures that will be characterized by better thermal characteristics than ceramic monolithic catalysts and lower pressure drop than packed beds will be continued (Tronconi et al., 2006; Kołodziej et al., 2001, 2004; Stringaro et al., 1998). ***The author suggests that one of the most promising structures for carrying exothermic reactions is the one based upon CBMiM static mixer. Surface area of its elements is ca. 260-300 m^2/m^3 compared with surface area of spherical catalyst pellets (dia. about 5 mm in a tube of dia. 26 mm) of ca. 300 m^2/m^3. Radial mixing in this mixer is very intensive and heat transfer with the tube wall is better than that for fixed-beds of conventional catalysts.*** However, in order to replace conventional catalytic reactors for the above processes effective methods for catalyst loading and replacement must be worked out as it has been done for particulate catalysts (Cybulski, 1981). Bundles of structural catalysts fixed to a kind of a grid would be appropriate for simultaneous loading of many tubes in multitubular reactors. The use of structured catalysts in the field of three-phase catalytic processes (bubble columns and trickle-bed reactors) for selective oxidations and hydrogenations, operated with recycle (loop reactors) is likely to expand. More equilibrium-limited reactions will be probably carried out in a way, which is realized in the case of synthesis of esters using sandwich structures.

Preliminary tests showed that the FSC on carbon fibers are very active in anodic oxidation of methanol and as such they might be useful in direct methanol fuel cells. The CFC with nanotubes was active and selective in hydrazine decomposition (source of energy in small jet engines); moreover that catalyst behaved much better than the commercial one in terms of attrition or damage during operation. The noble metal catalysts based upon any of the three supports exhibited a great activity in selective hydrogenation (including shape selectivity) of unsaturated hydrocarbons (2-butyne-1,4-diol, citral, cinnamaldehyde, banzaldehyde, acetylenic alcohols) and nitrites. Glass- and metal-based FSCs were successfully tested in oxidation of methane, propane and toluene at low concentrations (model systems for VOC incinerations).

The GFC appeared active in such oxidation at low and moderate temperatures (100-250 ^{0}C). The ZSM-GFC and the SMC turned out to be active and selective catalysts in hydroxylation of benzene with N_2O. The FSCs are likely to find applications, first of all, in the manufacture of fine chemicals. Boreskov Institute of Catalysis, Novosibirsk worked out geometrically structured fibrous catalysts based upon microfibers of high-silica fibrous carrier of 5-20 μm in diameter. The catalyst is claimed to be suitable for selective hydrogenation of polyunsaturated hydrocarbons, deep oxidation of carbon monoxide, organic and organohalogene compounds, sulfur dioxide oxidation, selective chlorination and oxychlorination of hydrocarbons, nitrogen oxide reduction, and reuse of gaseous and liquid wastes.

Stirred tank reactors dominate in production of **fine chemicals and pharmaceuticals** because of their versatility. Vast majority of catalytic three-phase processes are slurry processes run in such reactors. The development of versatile reactor units adapted to the use of easily exchangeable structured catalysts would allow for step by step replacement of stirred tank reactors in this branch of chemical industry with all advantages of structured catalysts and reactors. Cost of production of some structured catalyst is still higher than for conventional catalysts although progress in technology of their manufacture reduces those costs year by year. Further developments in the manufacture of structured catalysts are needed to increase spectrum of applications of structured catalysts in that sector. .

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?
Modeling	Mathematical modeling is the useful tool in identification of reactor deficiencies. To do modeling reliable data on transport phenomena must be at hand. Many papers addressing the interaction between the geometry of the contactor, flow, heat, and mass transfer characteristics and conversion of reactants (cold experiments) have been published but the knowledge on the subject is still insufficient	R&D projects carried out at universities in cooperation with manufactures of structured catalysts.
Design and scale-up methodologies	Multiplication of the elements that have been used in lab/pilot test reactors is now the very basic method for scale-up of structured reactors. This is not necessarily the way the best process conditions can be worked out.	R&D projects carried out at universities in cooperation with manufactures of structured catalysts and reactors and end users.
Optimization of structures	Utilization of catalytic surface depends mostly on flow phenomena: dead spaces and regions of less intensive flow must be identified. The size and the shape of structures should be optimized for particular applications.	R&D projects for departments of chemical engineering at universities addressed to studies on flow phenomena (CFD techniques).

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?
Low catalyst loading for structured catalysts of ASE type	The catalyst load in structured catalysts of APEs type is inherently low ranging from approximately 5 % to 20 %. Effectiveness factor is, however, high due to a thin catalytic layer and, consequently, short diffusion path. New structures should be developed that would allow to increase the interfacial surface area.	R&D projects carried out at universities in cooperation with manufactures of structured catalysts and reactors and end users. Particular attention should be paid to the structure that is mentioned Table 1 (row 6)
Incomplete bed utilization	This is characteristic for PPRs. Reactants penetrate the catalyst bed by diffusion that is a slow process. For relatively fast reactions bed utilization ranges therefore between 0.2 and 0.8. Since diffusion is a slow process the PPR is suitable only for processes occurring in kinetic regime. A proper design of the catalyst particles and catalytic modules can result in increasing the bed utilization.	R&D projects carried out at universities in cooperation with manufactures of structured catalysts and reactors and end users.
High sensitivity to non-uniform of flow at the reactor inlet	There is free flow of reactants through the passages resulting in the very low pressure drop. This is advantageous from the viewpoint of consumption of energy for pumping the reactants but it requires a very uniform flow distribution at the reactor's inlet otherwise non-uniform RTD will be observed with all consequences	Effective flow distributors must be designed and installed at the reactor's inlet. There are numerous commercial companies that specialize in this field.
Insertion and removal of structured catalysts in multitubular reactors	Loading, removal, and replacing of the catalyst is a time-consuming procedure for particulate catalyst. Therefore, special devices that enable loading and/or removal particles from many tubes simultaneously have been worked out. Those devices are, however, unsuitable for structured catalysts. This is one of the main obstacles in application of structured catalysts foe carrying out fast and highly exothermic reactions.	R&D projects carried out at universities in cooperation with manufactures of structured catalysts and reactors and end users.
Manufacturing of catalysts for the B-SR	Hollow extrudates or ring-shaped pellets on wires, or mechanically to stack them on metal rods; extrusion of (silica or alumina) paste around the carrier wire or fiber (like the insulation material of electric cords); pilling of powders onto wire structures. Search for the best and the cheapest methods for manufacturing of B-SR catalysts should be continued	R&D projects for departments of catalysis and chemical engineering at universities

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
Moulijn, J.A., Kapteijn, F., Stankiewicz, A., 2004, Structured catalysts and reactors: a contribution to process intensification, Chapter 6 in Re-engineering	Review	General review

the chemical processing plant. Process intensification, Stankiewicz, A., Moulijin, J.A., eds., Marcel Dekker, New York		
Cybulski, A. and Moulijn, J.A., 1994, Modelling of Heat Transfer in Metallic Monoliths Consisting of Sinusoidal Cells, *Chem. Eng. Sci.*, 49 (1), 19-27.	Research paper	Heat transfer in MTIPs studied
Stringaro, J.-P., Collins, P., Basiler, O., 1998, Open cross-flow-channel catalysts and catalyst supports, Chapter 14 in Structured catalysts and reactors, Cybulski, A. and Moulijn, J.A., eds, Marcel Dekker, New York	Review	OCFS of Sulzer reviewed and investigated
Groppi, G., Beretta, Al., Tronconi, E., 2006, Monolithic catalysts for gas-phase syntheses of chemicals, Chapter 8 in Structured catalysts and reactors, 2nd ed., Cybulski, A. and Moulijn, J.A., eds, Taylor&Francis, Boca Raton	Review	An extensive review of structured catalysts in application to chemical processes
Xiaoding Xu, Moulijn, J.A., 1998, Transformation of a structured carrier into structured catalyst, Chapter 21 in Structured catalysts and reactors, Cybulski, A. and Moulijn, J.A., eds, Marcel Dekker, New York; 2006, Chapter 21 in Structured catalysts and reactors, 2nd ed., Cybulski, A. and Moulijn, J.A., eds, Taylor&Francis, Boca Raton	Review	Review of methods that are used to prepare structured catalysts
Meille, V., 2006, Review on methods to deposit catalysts on structured surfaces, *Appl. Catal. A: General*, 315, 1-17	Review	Review of methods that are used to prepare structured catalysts
Twigg, M.V., Webster, D.E., 1998, Metal and metal-coated catalysts, Chapter 3 in Structured catalysts and reactors, Cybulski, A. and Moulijn, J.A., eds, Marcel Dekker, New York; 2006, Chapter 3 in Structured catalysts and reactors, 2nd ed., Cybulski, A. and Moulijn, J.A., eds, Taylor&Francis, Boca Raton	Review	Metallic structures reviewed
Held, W., Rohlfs, M., Maus, W., Swars, H., and Kaiser, F.W., 1994, *SAE Paper* 940932.	Technical paper	Data on EMITEC structures of MTIP-type
Brück, R., Diringer, J., Martin, U., and Maus, W., 1994, *SAE Paper* 940932.	Technical paper	Data on EMITEC structures of MTIP-type
Rebrov, E.V., de Croon, M.H.J.M, and Schauten, J.C., 2001, Design of a microstructured reactor with integrated heat-exchanger for optimum performance of a highy exothermic reaction, *Catal. Today*, 69 (1-4), 183-192.	Research paper	Microstructured PTC studied
Kołodziej, A., Krajewski, W., and Łojewska, J., 2004, Structured catalyst carrier for selective oxidation of hydrocarbons. Modeling and testing, *Catal. Today*, 91-92, 59-65; Kołodziej, A., Krajewski, W., and Dubis, A., 2001, Alternative solution for strongly exothermic catalytic reactions: a new metal-structured catalyst carrier, *Catal. Today*, 69, 115-120.	Research papers	Study on RC reported
Kotter, M., Lintz, H.G., Turek, T., 1992, Selective reduction of nitrogen oxide by use of the Ljungstrom air-heater as reactor: A case study, *Chem. Eng. Sci.*, 47, 2763	Research paper	PTC reactor
Götze, L., Bailer, O., Moritz, P., and von Scala C., 2001, Reactive distillation with Katapak®, *Catal. Today*, 69 (1-4), 201-208.	Research paper	Data on catalytic packings
Sie, S.T., Calis, H.P., Parallel-passage and lateral-flow reactors, 1998, Chapter 12 in Structured catalysts and reactors, Cybulski, A. and Moulijn, J.A., eds, Marcel	Review	Overview of PPRs and LFRs

Dekker, New York; 2006, Chapter 14 in Structured catalysts and reactors, 2nd ed., Cybulski, A. and Moulijn, J.A., eds, Taylor&Francis, Boca Raton		
Dautzenberg, F., Naber, J.E., and van Ginneken, A.J.J., et al., 1971, Shell's flue gas desulfurization process, *Chem. Eng. Progr.*, 67 (8), 86-91.	Research paper	The first information about industrial application of the SFGD process
Groenendaal, W., Naber, J.E., and Pohlenz, J.B., 1976, The Shell flue gas desulfurization process: Demonstration on oil- and coal-fired boilers, *A.I.Ch.E. Sympos Ser.*, 72 (156), 12-22.	Research paper	Report on the use of the PPR for gas desulfurization process
Samson, R., Goudriaan, F., Maaskant, O., and Gilmore, T., 1990, The design and installation of a low-temperature catalytic NO_x reduction system for fired heaters and boilers, paper presented at the 1990 Fall Int. Sympos. Of the Amsterdam Flame Research Committee, Oct. 8-10, San Francisco, CA.	Research paper	Data on PPR
Woldhuis, A., Goudriaan, F., Groeneveld, M.J., and Samson, R., 1991, Process for catalytic flue gas denoxing, paper presented at the Society of Petroleum Engineers Symposium on Health, Safety and Environment in oil and gas exploration and production, the Hague, Nov. 11-14.	Research paper	The first information about industrial application of the LFR
Goudriaan, F., Calis, H.P., van Dongen, F.G., and Groeneveld, M.J., 1991, Parallel-passage reactor for catalytic denoxing, paper presented at the 4th World Congress of Chemical Engineering, Karlsruhe, Germany, June 16-21.	Research paper	Data on PPR
Calis, H.P., Takács, K., Gerritsen, A.W., van den Bleek, C.M., 1998, Bead-string reactor, Chapter 13 in Structured catalysts and reactors, Cybulski, A. and Moulijn, J.A., eds, Marcel Dekker, New York	Review	Extensive overview on the B-SR
Cybulski, A., Catalytic wet air oxidation: Are monolithic catalysts and reactors feasible?, 2007, *Ind. Eng. Chem. Res.*, 46, 4007-4033	Review	Potential of structured catalysts and reactors for CWAO of wastewaters considered
Cybulski, A. Multitubular reactors (Polish), 1981, *Inżynieria i Aparatura Chemiczna*, 20 (3), 6-12	Review	

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.)

Patents granted to or applications for patents filed by Sulzer for structured packings have been omitted in Table 7. This kind of structures is described in more detail in Technology Report No. 2.2.8.1. There is a large number of patents on the subject. Hereunder, a selection of patents done by the author is presented.

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
US 2001038811, 2001	ABB Lummus Global Inc.	Structured packing with channels containing vortex generators
JP 10028871, 1998	Babcock Hitachi KK	Plate-like catalyst (see Fig. 7). a method of manufacture and use for treat-

		ing off-gases
JP 11319583, 1999	Babcock Hitachi KK	Plate-like catalytic structure covered with fabric of inorganic fibers
JP 10174884, 1998	Babcock Hitachi KK	A method of manufacturing plate-like catalytic structure
JP 5154351, 1993	Babcock Hitachi KK	Plate type denitration catalyst
US 4446250, 1984	Kawasaki Heavy Ind. Ltd.	Plate catalyst for denitrification (deNOxification)
PL 186589 B1, 2004; PL 186590 B1, 2004; PL 190333, 2005; PL, P-373210, 2005.	Institute of Chemical Engineering of the Polish Academy of Sciences	Structured catalyst carrier for exothermic processes
EU 1110605, 2001	European Vinyls Tech. Corp. (now, Ineos Vinyls UK Ltd.)	Metallic monolith catalyst support for selective gas phase reactions in tubular fixed bed reactors
US 20020038062, 2002	European Vinyls Corp. (now, Ineos Vinyls UK Ltd.)	Metallic monolith catalyst support for selective gas phase reactions in tubular fixed bed reactors
US 6881703, 2005	Corning Inc.	Thermally conductive (metallic) honeycombs for chemical reactors
WO 2005011889 A1, 2005 CN 1832820	Corning Inc.	Metal honeycomb substrates for chemical and thermal applications
WO 2005065187, 2005	Corning Inc.	Multitubular reactor with thermally conductive catalyst structures
US 2003100448, 2003	Corning Inc.	Thermally conductive (metallic) honeycombs for chemical reactors
US 2005142049, 2005 EP 1699552, 2006	Corning Inc.	Multitubular reactor with monolithic catalysts
WO 2006113196, 2006	Catacel Corp.	A reactor cartridge with heat transfer imrpoved
US 2006245982, 2006	Catacel Corp.	A method for insertion and removal of a catalytic cartridge
WO 2007015969, 2007	Catacel Corp.	A reactor having improved heat transfer
US 6203771, 2001	Allied Signal Inc.	Catalytic converter with plate fin elements.
EP 1440730, 2004	BASF AG	Structured packing with alternately packed catalyst-held and catalyst-free zones
DE 10208711, 2003	BASF AG	Catalytic ceramic packing for thermal separation and reaction of fluid mixtures
WO 2004058669, 2004	Oxeno Olefinchemie GmbH	Production of *t*-butanol by reactive distillation
EP1300387, 2004	Haltermann GmbH	Production of hydroxy-acid ester by reactive distillation
EP 1300413, 2003	Haltermann GmbH	Production of glycosides from sugars by reactive distillation
RU 2299190, 2007; RU 2292950, 2007;	Boreskov Institute of Cataly-	Oxidation of hydrocar-

RU 2289565, 2007	sis, Novosibirsk	bons, hydrogenation, chlorination, oxychlorination, selective hydrogenation of acetylenic hydrocarbons and reduction processes in the presence of catalyst on high-silica fibrous carrier
JP 2002113798, 2002	Nippon Steel Corp.	A metal fibrous support
EP 0562567, 1993	Topsøe Haldor AS	A catalyst for selective oxidation of ammonia on fibrous support
CZ 286616, 2000	Topsøe Haldor AS	A catalyst for preparation of aldehydes on fibrous support
JP 2003220327, 2005	BASF AG	Fixed-bed reactor for heterogeneously catalyzed reactions
US 3501897, 1970	Shell Oil Co.	Regards removal of sulfur compunds using the PPR
DE 1907027, 1969	Shell Internationale Research Mij., N.V.	Desulfurization and the PPR for performikng the process
DE 2030677; 1970	Shell Internationale Research Mij., N.V.	Device for contacting gases with a solid: The PPR
NL 9000454; 1989	Albert Gerritsen.	The B-SR
WO 9633017, 1996	Delft Univ. of Technol.	The B-SR
WO 99/48604, 1999	ABB Lummus Global Inc.	Fixed-Bed Catalytic Reactor with catalyst particles placed in monolith channels

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**
Sulzer CHEMTECH	Switzerland	OCFSs, sandwich structures, structural packings
Babcock Hitachi	Japan, US	Structured catalysts of PTC-type for cleaning flue gases
ABB Lummus Global	US	Fundamental and engineering studies on structured catalysts
BASF AG	Germany	Structural packings
Shell International	The Netherlands	R&D on applications of PPR and LFR
Corning Inc.	US	Structured catalysts, prevailing ceramic but also metallic
European Vinyls Tech. Corp. (now, Ineos Vinyls UK Ltd.)	GB	Metallic monolith catalyst support for selective gas phase reactions in tubular fixed bed reactors
Catacel Corp.	US	A reactor having improved heat transfer
Delft University of Technology (Prof. J.A.Moulijn, Prof. F. Kapteijn)	The Netherlands	Fundamental and engineering studies on structured catalysts and

		reactors (PPR, LFR, B-SR)
University of Stuttgart	Germany	Studies on transport phenomena in OCFS Sulzer structures
University of Bath, Dept. Chem. Eng. (Prof. S. Kolaczkowski)	GB	Fundamental and engineering studies on structured catalysts
Politecnico di Milano, Department of Industrial Chemistry and Chemical Engineering (Prof. E. Tronconi, Prof. P. Forzatti)	Italy	Fundamental and engineering studies on structured catalysts for exothermic reactions and SCR
Ecole Polytechniquue Fédérale de Lausanne; Swiss Federal Institute of Technology (Lausanne), Institute of Chemical Engineering (Prof. A. Renken)	Switzerland	Extensive studies on fiber based structured catalysts
Åbo Akademi University, Lab. Industrial Chemistry, Process Chemistry Centre, Turku (Prof. T. Salmi)	Finland	Fundamental and engineering studies on structured catalysts and reactors
Institute of Chemical Engineering of the Polish Academy of Sciences, Gliwice (Dr. A. Kołodziej, Prof. W. Krajewski)	Poland	Fundamental and engineering studies on structured catalysts for exothermic reactions

5. Stakeholders

5.1 Suppliers and developers

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

There is a great number of suppliers of structured catalysts and plants using them. Hereunder, the best known suppliers and some other exemplary companies are given.

Table 9. Supplier and developers

Institute/Company	Country	Remarks
Sulzer CHEMTECH, Winterthuur	Switzerland, worldwide	A supplier of OCFSs (SMX, SMXL, SMXS, SMV, SMF, and SMR) and structured packings that is experienced in the manufacture and R&D
Koch-Glitsch	US, worldwide	A supplier of structured packings
Julius Montz GmbH, Hilden	Germany	A supplier of structures of the type Montz-Pak BS (Multipak®)
Distillation Alliance (Distall)	GB	A supplier of structured packings
BASF Catalyst Division (Engelhard by June 2006)	Germany	A supplier of structured catalysts for deNOxification and VOC incineration
Johnson Matthey	GB, US	A supplier of structured catalysts for deNOxification and VOC incineration
Hitachi Zosen Fukui	Japan	A supplier of structured plate-type catalysts for deNOxification and VOC incineration
Babcock Power Environmental	US	A supplier of SCR plants
Ehovoc Oy, Ecocat Oy	Finland	A supplier of structured catalysts and plants for VOC incineration
EmeraChem	US	ADCAT™ VOC oxidation catalysts

Trunett Environmental Tech. Co. Ltd.	US	A supplier of structured catalysts for VOC incineration
Shell International, Amsterdam	The Netherlands	Fundamental and engineering studies on structured catalysts and reactors (PPR, LFR, B-SR)

5.2 End users

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

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

ASEs (mainly MTIPs, and PTCs) are well developed and the number of industrial applications for oxidation of VOCs and reduction of NO_x in off-gases will continually increase. The ACCPs (PPR, LFR, and B-Sr) will lose in competition with the other structured reactors for cleaning flue gases since they are less effective as far as catalyst utilization is concerned.

The use of structured catalysts in the field of three-phase catalytic processes (bubble columns and trickle-bed reactors) for selective oxidations and hydrogenations, operated with recycle (loop reactors) is likely to expand. It may be expected that in the future more complex structure of this kind will be developed to realize the full potential of structured catalysts. More equilibrium-limited reactions will be probably carried out in a way, which is realized in the case of synthesis of esters using sandwich structures. A high separation efficiency of structured packings makes them particularly useful for carrying catalytic reactions with a simultaneous separation of components by distillation.

Structured catalysts and reactors for carrying out reactions with high thermal effect are promising and close to industrial applications. More efforts are necessary to work out device(s) for quick insertion and removal of such structured catalysts simultaneously from many tubes of a multitubular reactor.

The FSCs are likely to find more applications, first of all, in the manufacture of fine chemicals.