EUROPEAN PATENT SPECIFICATION

PROCESS FOR THE DEHYDROGENATION OF ETHYLBENZENE TO STYRENE
VERFAHREN ZUR DEHYDRIERUNG VON ETHYLBENZOL ZU STYROL
PROCEDE DE DESHYDROGENATION D’ETHYLBENZENE EN STYRENE

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE

(30) Priority: 30.09.1999 IT MI992031

(43) Date of publication of application: 26.06.2002 Bulletin 2002/26

(73) Proprietor: SNAMPROGETTI S.p.A. 20097 San Donato Milanese (Milano) (IT)

(72) Inventors:
• IEZZI, Rodolfo I-20097 San Donato Milanese (IT)
• SANFILIPPO, Domenico I-20067 Paullo (IT)

(74) Representative: De Gregori, Antonella et al Ing. Barzano & Zanardo Milano S.p.A. Via Borgonuovo 10 20121 Milano (IT)

(56) References cited:

Note: Within nine months from the publication of the mention of the grant of the European patent, any person may give notice to the European Patent Office of opposition to the European patent granted. Notice of opposition shall be filed in a written reasoned statement. It shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention.)
The present invention relates to a process for the dehydrogenation of ethylbenzene to styrene in a fluid-bed reactor/regenerator system, in the presence of a catalyst based on an iron oxide and further promoters, selected, e.g., from metal oxides such as alkaline oxides, earth-alkaline metal oxides and/or oxides of the metals of the group of lanthanides, supported on a modified alumina.

Styrene is an important intermediate which can be used in the preparation of plastic materials and rubbers. More specifically, styrene is used for the production of polystyrenes (GPPS crystals, high impact HIPS and expandable EPS), acrylonitrile-styrene-butadiene (ABS) and styrene-acrylonitrile (SAN) copolymers and styrene-butadiene rubbers (SBR).

The dehydrogenation reaction of ethylbenzene to styrene has a few particular characteristics which should be taken in account for the technological design. The first lies in the fact that the reaction is controlled by thermodynamic equilibrium and consequently the conversion per passage is not total. The dehydrogenation degree increases with a rise in the temperature and with a decrease in the total pressure, the reaction taking place at a constant pressure, with an increase in the volume. In order to obtain economically acceptable conversions, it is therefore necessary to carry out the reaction at temperatures generally ranging from 540 to 630°C.

The use of high temperatures however stimulates side reactions characterized by a greater activation energy with respect to the dehydrogenation value. As a result of this, more or less significant quantities of by-products mainly consisting of toluene, benzene, coke and light products are formed together with the main product.

It is therefore necessary to use a catalyst capable of directing the reaction towards the desired product. The last important aspect consists in the fact that the reaction is extremely endothermic, with a reaction heat equal to 28 Kcal/moles of styrene corresponding to 270 Kcal/kg of styrene produced.

The high heat required and the high thermal levels at which it must be exchanged greatly influence the technological design.

The technologies at present commercialized (Final Badger and Lummus/UOP Classic SM processes) satisfy, the demands imposed by the thermodynamics of the reaction by means of processes which use a bulk catalyst prevalently based on iron oxide and promoted with alkalis, and which comprise the use of:

- several adiabatic reactors in series, with intermediate heating steps at a temperature ranging from 540°C to 630°C and with contact times in the order of tenths of a second;
- radial flow reactors which operate under vacuum at a pressure ranging from 30.39 to 50.65 kPa (absolute Pascal) (0.3 to 0.5 ata) (absolute atmospheres); and
- water vapor which is fed with the charge to be dehydrogenated.

Water is the main component in the charge fed to the reactor. The typical molar concentration is 90%, even if higher concentrations are often adopted to lengthen the chemical life of the catalyst.

The vapor has the function of:

- reducing the partial pressure of the products and therefore favorably shifting the thermodynamic equilibrium;
- contributing to the removal of the coke which is deposited on the surface of the catalyst, there being no regeneration of the catalyst with air;
- supplying the heat necessary for the dehydrogenation of the ethylbenzene;
- slowing down the aging of the catalyst.

Operating with these technologies, conversions ranging from 60 to 65% are obtained, with a selectivity to styrene higher than 90% by weight.

These processes however have the following disadvantages:

- use of large quantities of vapor (H₂O/EB = 9.0-10 molar) superheated with temperatures higher than 700°C; this impels the use of superheating ovens and therefore high investment costs;
- aging of the catalyst and consequently the necessity of substituting it after 18-36 months of operation; this involves stopping the unit and consequently interrupting the production for the period necessary for substituting the catalyst;
- non-optimized energy recovery; present technologies, in fact, only comprise the recovery of the sensitive vapor heat and not that of the latent heat;
- carrying out the reaction under vacuum (average absolute pressure of 40.52 kPa (abs Pa) (0.4 ata)) and therefore in extremely diluted phase in EB; the partial. EB pressure is on an average equal to 40.52 kPa (abs Pa) (0.04 ata).
It has now been found that it is possible to overcome these drawbacks by means of a process which uses a fluid-bed reactor/regenerator system and a catalyst based on iron oxide supported on a microspheroidal alumina modified with silica and further metal oxides as promoters.

The process of the present invention has considerable economic advantages, in particular:

- thermal profile of the reactor favorable for the reaction thermodynamics;
- the heat is directly transferred to the reaction by the regenerated catalyst, superheating ovens are therefore not required for the thermal exchange and the strong remixing of the fluidized bed prevents the formation of hot spots which would lower the selectivity;
- the possibility of recycling the hydrogen;
- the plant can be run with great flexibility in terms of actual productive capacity with respect to that projected;
- the dehydrogenation reaction and the regeneration take place in physically separated zones; this avoids the mixing of hydrocarbon streams with oxygen streams;
- the process is carried out at a pressure which is atmospheric or slightly higher; as a result, there are no air infiltrations from the outside in the reaction zone;
- the molar concentration of the inert gas/ethylbenzene in the feeding is much lower with respect to commercial technologies;
- it is not necessary to effect any specific treatment for reducing the emissions of gas pollutants; and
- the possibility of operating without water vapor without there being any chemical deterioration in the catalyst.

Japanese patent application 7-328,439 discloses a process for the dehydrogenation of ethylbenzene in the presence of a catalyst which consists of alumina, carrying a complex of potassium ferrate and possibly rare earth metal oxides, modified by basic metallic oxide addition. Said catalyst shows activity when operated in the presence of water but no data are given in said patent application about the performances of the catalyst in the absence of water, as co-feed of ethylbenzene, nor the effect of ageing is detailed. Surprisingly, it was found that through a partial modification of the alumina carrier by silica it was possible to improve significantly the catalytic performances in dehydrogenation yield, with evident advantages. In the same time, the mechanical resistance of the catalyst itself is improved by silica modification making it more suited to fluid bed operations. Furthermore, the catalyst is also able to operate with nitrogen other than with water.

In accordance with this, the present invention relates to a process for dehydrogenating ethylbenzene to styrene which essentially consists in:

(a) reacting ethylbenzene mixed with an inert product, in a fluid-bed reactor, in the presence of a catalytic system consisting of iron oxide and promoters supported on alumina modified with 0.01-10% by weight of silica and operating at a temperature ranging from 400 to 700°C, at a total pressure of 10.13 to 303.9 kPa (abs Pa) (0.1 to 3 ata) and with a GHSV space velocity ranging from 50 to 10,000 h⁻¹ (normal liters of the mixture ethylbenzene and inert gas/h x liter of catalyst); and
(b) regenerating the catalyst in a regenerator by burning the coke deposited on its surface at a temperature exceeding 400°C.

The catalytic system used in the process of the present invention consists of:

(1) 1-60% by weight, preferably 1-20%, of iron oxide;
(2) 0.1-20% by weight, preferably 0.5-10%, of at least one alkaline or alkaline earth metal oxide;
(3) 0-15% by weight, preferably 0.1-7% of a second promoter consisting of at least one rare earth oxide;
(4) the complement to 100 being a carrier consisting of a microspheroidal alumina with a diameter selected from those in delta, theta phase or their mixtures, in theta + alpha phase or delta + theta + alpha phase, modified preferably with 0.08-5% by weight of silica.

The carrier has an average particle diameter and particle density such that the final product can be classified as Group-A according to Geldart (Gas Fluidization Technology, D. Geldart, John Wiley & Sons) and a surface area of less than 150 m²/g (BET).

Alkaline metal preferably used as first promoter in the present invention is potassium. Preferred second promoters belonging to the rare earth metals are cerium, lanthanum and praseodymium.

An example of catalyst according to the present invention consists of:

(1) 5-50% by weight of iron oxide;
(2) 0.5-10% by weight of a promoter expressed as oxide;
(3) the complement to 100 being a carrier consisting of a microspheroidal alumina with a diameter ranging from 50 to 70 microns selected from those in delta, theta phase or their mixtures, in theta + alpha phase, modified preferably with 0.08-3% by weight of silica. The process for preparing the catalytic system described above can be essentially carried out by means of the following steps:

- preparation of solutions based on derivatives of the components of the catalytic system;
- dispersion of the solutions on carriers as defined above;
- drying of the solids obtained;
- calcination of the dried solids at a temperature ranging from 500 to 900°C.

The dispersion of the catalyst components on the carrier can be carried out using conventional techniques such as impregnation, ion exchange, vapor deposition or surface adsorption.

The "incipient wetness" impregnation technique is preferably used.

According to a preferred embodiment, the catalyst is prepared by:

(a) addition of an aliquot of the promoters to the carrier;
(b) drying at 100-150°C and, optionally, calcination of the dried solid at a temperature not exceeding 900°C;
(c) dispersion of the iron oxide and remaining aliquot of the promoters on the modified carrier (a);
(d) drying at 100-150°C and calcination of the dried solid at a temperature ranging from 500 to 900°C.

Steps c) and d) can be repeated several times.

Nitrogen, methane, hydrogen or water vapor can be used as the gaseous inert product, in a volumetric ratio inert gas/ethylbenzene ranging from 1 to 6, preferably from 2 to 4. Methane and nitrogen are preferably used.

According to a further embodiment of the process of the present invention, the ethylbenzene can be co-fed to the reactor with a paraffin selected from ethane, propane, isobutane, in order to obtain the contemporaneous dehydrogenation of the co-fed products to give styrene and the corresponding olefins respectively.

In particular when the ethylbenzene is fed with ethane, the process can be carried out as described in U.S. patent 6,031,143.

According to a further embodiment of the process of the present invention, ethylene can be recycled to an alkylation unit together with a stream of benzene to give ethylbenzene.

In the reactor-regenerator system, the catalyst circulates continuously, in fluidized state, between the reactor and regenerator, thus allowing the process to be carried out in continuous.

The catalyst is maintained in a fluidized state in the reactor by the reagent mixture (inert gas/ethylbenzene), which enters the catalytic bed from below, by means of an appropriate distribution system.

The reacted gas, after passing through a system of cyclones or another powder separation system, leaves the reactor from above. The gas can then be sent to a heat exchanger for the preheating of the feeding and subsequently to the separation section where the styrene produced is recovered, whereas the non-reacted charge is recycled to the dehydrogenation reactor and the reaction by-products (light hydrocarbons and hydrogen) are recovered and used in the regenerator as fuel gas.

The catalyst moves in fluidized state in the reactor, in countercurrent with respect to the gas phase. It enters the catalytic bed from above, through a distributor which disperses it equally on the surface of the bed, and it leaves the reactor from below, passing by gravity into a desorption zone where the moving and desorption of the intraparticle gas take place, nitrogen or methane being introduced from below, so that the moved or desorbed gas re-enters the reactor, thus avoiding losses in reagents or products.

It is preferable to operate in the fluid-bed reactor as follows:

- at a temperature ranging from 450 to 650°C in relation to the desired reaction; the temperature is maintained within the pre-selected values by regulating the flow-rate of the regenerated catalyst;
- at a pressure which is atmospheric or slight higher;
- at a GHSV space velocity ranging from 100 and 1000 h⁻¹, preferably from 150 to 300 h⁻¹; and
- with a residence time of the catalyst in the fluid bed ranging from 5 to 30 minutes, and in the desorption zone from 0.2 to 10 minutes.

According to an embodiment of the process of the present invention, grids can be horizontally arranged inside the reactor, at a distance of 20 to 200 cm from each other, and with a free area ranging from 10 to 90%, preferably...
from 20 to 40%. The purpose of the grids is to prevent the gas and catalyst from re-mixing, so that the gas flow inside the reactor resembles a plug-flow. The use of these grids allows maximization of the conversion of ethylbenzene and selectivity to styrene.

[0038] The selectivity of the reaction can be further improved by the longitudinal thermal profile which is established along the catalytic bed, with the maximum temperature in the upper part where the regenerated catalyst arrives and the minimum temperature in the lower part. The temperature difference along the bed preferably ranges from 15 to 65°C.

[0039] In order to optimize the longitudinal thermal profile, the regenerated catalyst can be distributed at various heights of the catalytic bed.

[0040] The fluidized catalyst is subsequently sent to the regenerator through a pneumatic transport system consisting of:

- a transport line with at least one zone in which the catalyst moves downwards by the introduction of suitable quantities of gas at appropriate heights, and
- a zone in which the catalyst moves upwards until it reaches the upper part of the catalytic bed, by the introduction of gas at the base of the raiser.

[0041] The regenerator preferably has similar dimensions to those of the reactor to maintain the catalyst for a period sufficient for its regeneration.

[0042] The regeneration of the catalyst is carried out by the combustion of coke with air and oxygen, whereas its heating is effected with the use of methane, a fuel gas, or by-products of the dehydrogenation reaction, at a temperature higher than the average reaction temperature.

[0043] The movement of the gas and solid takes place in countercurrent also in the regenerator: air enters the bottom of the catalytic bed, whereas the fuel gas is introduced at suitable heights along the bed.

[0044] The gas leaving the regenerator, substantially consisting of nitrogen and combustion products, is passed through a system of cyclones, or other system, situated in the upper part of the apparatus, to separate the entrained powders and is then sent to a heat exchanger to preheat the combustion air.

[0045] Before being discharged into the atmosphere, these gases can be treated with a filter system or other devices for reducing the powder content to a few tenths of mg per Nm³ of gas.

[0046] In the regenerator, it is preferable to operate at atmospheric pressure or slightly higher, at a space velocity ranging from 100 to 1,000 h⁻¹ and with a residence time of the catalyst ranging from 5 to 60 minutes, preferably from 20 to 40 minutes.

[0047] The regenerated and reheated catalyst is sent to the reactor by means of a pneumatic system having the characteristics described above.

[0048] The use of the reactor-regenerator system has the following advantages:

- the possibility of keeping the operating parameters and catalytic performances constant for the whole technical life of the plant;
- the heat is transferred to the reaction directly by the regenerated catalyst; there is therefore no need for superheating ovens for the thermal exchange and the strong re-mixing of the fluid bed prevents the formation of hot spots which would lower the selectivity;
- the hydrogen can be recycled;
- the process can be carried out in continuous without having to modify the operating parameters during the life of the plant;
- the reaction and regeneration take place in physically separated zones so that the hydrocarbon streams do not mix with streams containing oxygen;
- the molar concentration inert product/ethylbenzene in the feeding is much lower with respect to the commercial technologies.

[0049] With reference to figure 1, a possible application of the reactor-regenerator scheme is provided, which uses the catalyst based on supported iron oxide.

[0050] The liquid stream of ethylbenzene (1), consisting of fresh and recycled feeding, at room temperature and a pressure of 263.38 kPa (abs Pa) (2.6 ata), is vaporized in the evaporator (2), preheated to about 420°C in the gas-gas exchanger (3), mixed in a suitable mixer (4) with a stream (5) prevalently consisting of nitrogen and whose origin is described hereunder, and fed to the reactor (6) by means of an appropriate distributor situated in the lower part. The stream (7), effluent from the reactor at a temperature of 600°C, at a pressure of 135.74 kPa (abs Pa) (1.34 ata), essentially consisting of nitrogen, styrene, hydrogen and non-reacted ethylbenzene, undergoes a first cooling in the gas-gas exchanger (3) and a second cooling in the gas-gas exchanger (8), from which it flows at a temperature of 320°C. This stream then passes through the filter system (9) to eliminate the fine particles entrained and is subsequently
cooled with water to a temperature of 40°C in the exchanger (10). The mixture becomes biphasic at this temperature as a result of the partial condensation of the hydrocarbon.  

- stream (15) consisting of pure styrene (product);  
- stream (16) consisting of ethylbenzene, which is recycled to the dehydrogenation;  
- stream (17) essentially consisting of nitrogen and hydrogen, containing light hydrocarbons;  
- stream (18) essentially consisting of benzene and toluene;  
- stream (19) consisting of heavy hydrocarbon by-products.

The following examples, whose sole purpose is to describe this invention in greater detail, should in no way
be considered as limiting the scope of the invention.

Example 1

[0067] A microspheroidal pseudoboehmite to which silica (1.2% by weight) has been added, is prepared, with a particle diameter ranging from 5 to 300 µ, by the spray drying of a sol of hydrated alumina and Ludox silica. A sample of pseudoboehmite is calcined at 450°C for 1 hour and then at 1190°C for 4 hours in a stream of dry air. The product obtained, consisting of δ, θ and α transition alumina, has a specific surface of 34 m²/g and a porosity of 0.22 cc/g.

[0069] 150 g of microspheroidal alumina are impregnated, using the "incipient wetness" procedure, with 33 ml of an aqueous solution containing 7.8 g of KNO₃ (titer 99.5%) in deionized water, maintained at a temperature of 25°C. The impregnated product is dried at 80°C for 1 night and then calcined, in a stream of dry air, at 650°C for 4 hours in a stream of dry air. The concentration of potassium, expressed as oxide, with respect to the calcined product, is equal to 2.4% by weight.

[0071] An impregnating solution is then prepared by dissolving in 23 ml of deionized water: 56.2 g of Fe(NO₃)₃·9H₂O (titer 99% by weight) and 6.7 g of KNO₃ (titer 99.5% by weight). The solution, heated to 50°C to complete the dissolution of the salts, is maintained at this temperature for the whole duration of the impregnation.

[0072] The alumina modified with potassium oxide (153.6 g) is impregnated with an aliquot (48 g) of impregnating solution, dried at 120°C for 4 hours and impregnated again with the remaining aliquot of impregnating solution. The impregnation, drying and calcination are carried out with the same procedure described in example 1.

[0073] The impregnated product is dried at 120°C for a night and finally calcined at 700°C for 4 hours. The weight composition of the formulate is the following: 6.6% Fe₂O₃, 4% K₂O and carrier the complement to 100.

[0075] The formulae was tested in the dehydrogenation reaction of ethylbenzene to styrene and the average results, after a test run of 100 hours, are indicated in table 1.

Example 2

[0076] 150 g of microspheroidal alumina obtained as described in example 1, are impregnated with a solution containing: 56.3 g of Fe(NO₃)₃·9H₂O (titer 99% by weight) and 14.2 g of KNO₃ (titer 99.5% by weight).

[0077] The impregnation, drying and calcination are carried out with the same procedure described in example 1.

[0078] The impregnated product is dried at 120°C for a night and finally calcined at 700°C for 4 hours. The weight composition of the formulate is the following: 6.6% Fe₂O₃, 4% K₂O and carrier the complement to 100.

[0080] The same procedure is adopted as in example 2, but using an impregnating solution containing: 55.2 g of Fe(NO₃)₃·9H₂O (titer 99% by weight) and 6.7 g of KNO₃ (titer 99.5% by weight). The impregnation, drying and calcination are carried out with the same procedure described in example 1.

[0081] The impregnated product is dried at 120°C for a night and finally calcined at 700°C for 4 hours. The weight composition of the formulate is the following: 6.6% Fe₂O₃, 1.9% K₂O and carrier the complement to 100.

Example 3

[0082] The weight composition of the formulate is the following: 6.5% Fe₂O₃, 0.8% K₂O and carrier the complement to 100.

Example 4

[0083] The same procedure is adopted as in example 2, but using an impregnating solution containing: 53.9 g of Fe(NO₃)₃·9H₂O (titer 99% by weight) and 2.8 g of KNO₃ (titer 99.5% by weight). The weight composition of the formulate is the following: 6.5% Fe₂O₃, 0.8% K₂O and carrier the complement to 100.

Example 5

[0084] The dehydrogenation average results of ethylbenzene, after a test run of 100 hours, are indicated in table 1.

[0086] The dehydrogenation average results of ethylbenzene, after a test run of 100 hours, are indicated in table 1.

Example 5

[0087] The first aliquot is added on alumina alone which is then dried at 120°C for 4 hours after impregnation. The dried product is then impregnated with a further 45 g of mother impregnating solution in each step.
The weight composition of the formulate is the following: 10.3% $\text{Fe}_2\text{O}_3$, 4% $\text{K}_2\text{O}$ and carrier the complement to 100.

The dehydrogenation average results of ethylbenzene, after a test run of 100 hours, are indicated in table 1.

Example 6

A carrier having a surface area of 100 $\text{m}^2/\text{g}$ has been prepared by calcining the same pseudoboehmite containing silica of example 1 at 1060°C.

200 g of such a carrier are impregnated with a solution containing 57.05 g of $\text{Fe(NO}_3\text{)}_3.9\text{H}_2\text{O}$ (titer 99% b.w.) and 17.23 g of $\text{KNO}_3$ (titer 99.5% b.w.), 2.97 g of $\text{Ce(NO}_3\text{)}_3.6\text{H}_2\text{O}$ and 2.93 g of $\text{La(NO}_3\text{)}_2.6\text{H}_2\text{O}$ at a temperature of 60°C. The impregnation is carried out in a unique step.

The impregnated material is dried at 120°C for 4 hours, then calcined at 750°C for 4 hours.

The weight composition of the formulate is the following: 5.0% $\text{Fe}_2\text{O}_3$, 3.68% $\text{K}_2\text{O}$, 0.5% $\text{Ce}_2\text{O}_3$, 0.5% $\text{La}_2\text{O}_3$ and carrier the complement to 100.

The dehydrogenation results of ethylbenzene, during a test run of 150 hours, are shown in table 2.

Example 7 (Comparative)

In order to demonstrate the promoting effect of silica in the carrier, a sample has been prepared according to the same procedure of example 6 but based on a carrier, free of silica, having a surface area of 104 $\text{m}^2/\text{g}$.

The dehydrogenation average results of ethylbenzene, during a test run of 188 hours, are indicated in Table 2.

Example 8

The contemporaneous dehydrogenation of ethylbenzene and ethane is carried out in the micro-reactor described above, at a temperature of 600°C, using the catalyst of example 1.

Table 3 enclosed indicates the operating parameters and results obtained.
### TABLE 1

<table>
<thead>
<tr>
<th>Ex.</th>
<th>Fe₂O₃%</th>
<th>K₂O%</th>
<th>T°C</th>
<th>EB%vol</th>
<th>H₂O%vol</th>
<th>N₂%vol</th>
<th>kPa</th>
<th>pEB</th>
<th>Conversion</th>
<th>Selectivity</th>
<th>Styrene yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ethylbenzene %</td>
<td>Styrene mol.%</td>
<td>mol.%</td>
</tr>
<tr>
<td>1</td>
<td>6.6</td>
<td>4</td>
<td>540</td>
<td>20</td>
<td>0</td>
<td>80</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>50</td>
<td>93</td>
<td>47</td>
</tr>
<tr>
<td>1 bis</td>
<td>6.6</td>
<td>4</td>
<td>540</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>42</td>
<td>96</td>
<td>40</td>
</tr>
<tr>
<td>1 ter</td>
<td>6.6</td>
<td>4</td>
<td>572</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>53</td>
<td>87</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>4</td>
<td>545</td>
<td>20</td>
<td>0</td>
<td>80</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>50</td>
<td>89</td>
<td>45</td>
</tr>
<tr>
<td>2 bis</td>
<td>6.6</td>
<td>4</td>
<td>570</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>52</td>
<td>85</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>6.6</td>
<td>1.9</td>
<td>550</td>
<td>20</td>
<td>0</td>
<td>80</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>50</td>
<td>87</td>
<td>44</td>
</tr>
<tr>
<td>3 bis</td>
<td>6.6</td>
<td>1.9</td>
<td>580</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>50</td>
<td>84</td>
<td>42</td>
</tr>
<tr>
<td>4</td>
<td>6.5</td>
<td>0.8</td>
<td>580</td>
<td>20</td>
<td>0</td>
<td>80</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>50</td>
<td>82</td>
<td>41</td>
</tr>
<tr>
<td>4 bis</td>
<td>6.5</td>
<td>0.8</td>
<td>580</td>
<td>20</td>
<td>17</td>
<td>63</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>31</td>
<td>79</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>10.4</td>
<td>4</td>
<td>550</td>
<td>20</td>
<td>0</td>
<td>80</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>50</td>
<td>87</td>
<td>44</td>
</tr>
<tr>
<td>5 bis</td>
<td>10.4</td>
<td>4</td>
<td>572</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>51</td>
<td>84</td>
<td>43</td>
</tr>
</tbody>
</table>

Examples 1bis-5bis are comparative examples carried out in the presence of water

* 111.43 kPa (abs Pa)
### TABLE 2

<table>
<thead>
<tr>
<th>Ex.</th>
<th>Catalyst composition (%)</th>
<th>Feed (%V)</th>
<th>Conv. EB %</th>
<th>Select. Styrene % mol</th>
<th>Yield Styrene % mol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe₂O₃</td>
<td>K₂O</td>
<td>Ce₂O₃</td>
<td>La₂O₃</td>
<td>T°C</td>
</tr>
<tr>
<td>6</td>
<td>5.0</td>
<td>3.6</td>
<td>0.5</td>
<td>0.5</td>
<td>560</td>
</tr>
<tr>
<td>6</td>
<td>5.0</td>
<td>3.6</td>
<td>0.5</td>
<td>0.5</td>
<td>560</td>
</tr>
<tr>
<td>7</td>
<td>5.0</td>
<td>3.6</td>
<td>0.5</td>
<td>0.5</td>
<td>560</td>
</tr>
<tr>
<td>7</td>
<td>5.0</td>
<td>3.6</td>
<td>0.5</td>
<td>0.5</td>
<td>580</td>
</tr>
<tr>
<td>7</td>
<td>5.0</td>
<td>3.6</td>
<td>0.5</td>
<td>0.5</td>
<td>560</td>
</tr>
</tbody>
</table>

* 111.43 kPa (abs Pa)
<table>
<thead>
<tr>
<th>Feeding</th>
<th>Pressure (ata)</th>
<th>PEB</th>
<th>pEthane</th>
<th>Conversion</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB % vol.</td>
<td>Ethane % vol.</td>
<td>H₂O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>0</td>
<td>(1.1) *</td>
<td>0.11</td>
<td>0.99</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>0</td>
<td>(1.1) *</td>
<td>0.22</td>
<td>0.88</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
<td>0</td>
<td>(1.1) *</td>
<td>0.33</td>
<td>0.77</td>
</tr>
</tbody>
</table>

* 111.43 kPa (abs Pa)
Claims

1. A process for the dehydrogenation of ethylbenzene to styrene which comprises:
   
   (a) reacting the ethylbenzene mixed with an inert gas in a fluid-bed reactor, in the presence of a catalytic system consisting of iron oxide and promoters supported on alumina modified with 0.01-10% by weight of silica and operating at a temperature ranging from 400 to 700°C, at a total pressure of 10.13 to 303.9 kPa (abs Pa) (0.1 to 3 ata) and with a GHSV space velocity ranging from 50 to 10,000 h⁻¹ (normal liters of a mixture of ethylbenzene and inert gas/h x liter of catalyst); and
   
   (b) regenerating and heating the catalyst in a regenerator at a temperature exceeding 400°C.

2. The process according to claim 1, wherein the catalyst consists of:
   
   (1) 1-60% by weight of iron oxide;
   (2) 0.1-20% by weight of at least one alkaline or alkaline earth metal oxide;
   (3) 0-15% by weight of a second promoter consisting of at least one rare earth oxide;
   (4) the complement to 100 being a carrier consisting of a microspheroidal alumina selected from those in delta, theta phase or their mixtures, in theta + alpha phase or delta + theta + alpha phase, modified with 0.08-5% by weight of silica.

3. The process according to claim 1 or 2, wherein the catalyst consists of:
   
   (1) 5-50% by weight of iron oxide;
   (2) 0.5-10% by weight of a metal promoter, expressed as oxide
   (3) the complement to 100 being a carrier consisting of a microspheroidal alumina with a diameter ranging from 50 to 70 microns selected from those in delta, theta phase or their mixtures, in theta + alpha phase or delta + theta + alpha phase, modified preferably with 0.08-3% by weight of silica.

4. The process according to any of the preceding claims, wherein the promoter is selected from alkaline, earth-alkaline metals or from the group of lanthanides.

5. The process according to claim 4, wherein the promoter is potassium oxide.

6. The process according to claim 4, wherein the promoters are potassium oxide, cerium oxide, lantanium oxide and praseodymium oxide.

7. The process according to any of the preceding claims, wherein the catalyst is obtained by:
   
   (a) addition of an aliquot of the promoter to the carrier;
   (b) drying at 100-150°C and, optionally, calcination of the dried solid at a temperature not exceeding 900°C;
   (c) dispersion of the iron oxide and remaining aliquot of promoter onto the carrier obtained in (a); and
   (d) drying at 100-150°C and calcination of the dried solid at a temperature ranging from 500 to 900°C;

   and wherein steps c) and d) can be repeated several times.

8. The process according to claim 1, wherein the inert gas is selected from nitrogen, methane, hydrogen and water vapor.

9. The process according to claim 8, wherein the inert gas is selected from nitrogen and methane.

10. The process according to claim 1, wherein the volumetric ratio inert gas/ethylbenzene ranges from 1 to 6.

11. The process according to claim 10, wherein the volumetric ratio ranges from 2 to 4.

12. The process according to claim 1, wherein the dehydrogenation reaction in step (a) is carried out at a temperature ranging from 450 to 650°C, at atmospheric pressure or slightly higher, at a GHSV space velocity ranging from 100 to 1,000 h⁻¹ and with a residence time of the catalyst ranging from 5 to 30 minutes.
The process according to claim 12, wherein the space velocity ranges from 150 to 300 h\(^{-1}\) and the residence time of the catalyst ranges from 10 to 15 minutes.

The process according to claim 1, wherein in step (b) the regeneration of the catalyst is carried out with air or oxygen whereas its heating is effected using methane, a fuel gas or by-products of the dehydrogenation reaction, operating at a higher temperature with respect to the average dehydrogenation temperature, at atmospheric pressure or slightly higher, at a space velocity ranging from 100 to 1,000 h\(^{-1}\) and with a residence time of the catalyst from 5 to 60 minutes.

The process according to claim 1, wherein in step a) the inert gas is a gaseous stream essentially consisting of nitrogen recovered from the combustion products of the regenerator.

The process according to claim 1, wherein in step a) the ethylbenzene is fed into the reactor mixed with a paraffin selected from ethane, propane or isobutane obtaining the contemporaneous dehydrogenation of the components of the mixture to give styrene and the corresponding olefins, respectively.

The process according to claim 16, wherein the ethylbenzene is fed to the reactor mixed with ethane obtaining the contemporaneous dehydrogenation of the components of the mixture to give styrene and ethylene respectively.

The process according to claim 17, wherein the ethylene is recycled to an alkylation unit together with a stream of benzene to give ethylbenzene.

Patentansprüche

1. Verfahren zur Dehydrierung von Ethylbenzol zu Styrol, darin bestehend, daß

   (a) das Ethylbenzol gemischt mit einem inerten Gas in einem Fließbettreaktor in Gegenwart eines katalytischen Systems aus Eisenoxid und Beschleunigern gestützt auf Aluminiumoxid modifiziert mit 0,01 bis 10 Gew.-% Siliziumdioxid zur Reaktion gebracht und bei einer Temperatur im Bereich von 400 bis 700 °C bei einem Gesamtdruck von 10,13 bis 303,9 kPa (abs.Pa) (0,1 bis 3 ata) und mit einer GHV-Raumgeschwindigkeit im Bereich von 50 bis 10,000 h\(^{-1}\) (Normalliter eines Gemisches von Ethylbenzol und inertem Gas/h x Liter Katalysator) gearbeitet wird und

   (b) der Katalysator in einem Regenerator bei einer Temperatur oberhalb von 400 °C regeneriert und erwärmt wird.

2. Verfahren nach Anspruch 1, bei dem der Katalysator besteht aus:

   (1) 1 bis 60 Gew.-% Eisenoxid,
   (2) 0,1 bis 20 Gew.-% zumindest eines Alkali- oder Erdalkalimetallocids,
   (3) 0 bis 15 Gew.-% eines zweiten Beschleunigers aus zumindest einem Seltenederioxid,

   (4) wobei das Komplement zu 100 ein Träger ist, der aus mikrophäroidalem Aluminiumoxid besteht, ausgewählt von solchen in Delta,Theta-Phase oder deren Gemischen, in Theta+Alpha-Phase oder Delta+Theta+Alpha-Phase, modifiziert mit 0,08 bis 5 Gew.-% Siliziumdioxid.

3. Verfahren nach Anspruch 1 oder 2, bei dem der Katalysator besteht aus:

   (1) 5 bis 50 Gew.-% Eisenoxid,
   (2) 0,5 bis 10 Gew.-% eines Metallbeschleunigers, ausgedrückt als Oxid,

   (3) wobei das Komplement zu 100 ein Träger aus einem mikrophäroidalen Aluminiumoxid mit einem Durchmesser im Bereich von 50 bis 70 Mikrometer ist, ausgewählt von solchen in Delta,Theta-Phase oder deren Gemischen, in Theta+Alpha-Phase oder Delta+Theta+Alpha-Phase, vorzugsweise modifiziert mit 0,08 bis 3 Gew.-% Siliziumdioxid.


5. Verfahren nach Anspruch 4, bei dem der Beschleuniger Kaliumoxid ist.

7. Verfahren nach einem der vorhergehenden Ansprüche, bei dem der Katalysator erhalten wird durch:

   (a) Zugabe einer Teilmenge des Beschleunigers zum Träger,
   (b) Trocknen bei 100 bis 150 °C und wahlweise Calcinierung des getrockneten Feststoffs bei einer Temperatur, die 900 °C nicht überschreitet,
   (c) Dispersion des Eisenoxids und Beibehaltung der Teilmenge des Beschleunigers auf dem Träger, erhalten in (a), und
   (d) Trocknen bei 100 bis 150 °C und Calcinierung des getrockneten Feststoffs bei einer Temperatur im Bereich von 500 bis 900 °C,

und wobei die Schritte c) und d) mehrere Male wiederholt werden können.

8. Verfahren nach Anspruch 1, bei dem das inerte Gas ausgewählt ist aus Stickstoff, Methan, Wasserstoff und Wasser dampf.


10. Verfahren nach Anspruch 1, bei dem das Volumenverhältnis inertes Gas/Ethylbenzol im Bereich von 1 bis 6 liegt.

11. Verfahren nach Anspruch 10, bei dem das Volumenverhältnis im Bereich von 2 bis 4 liegt.

12. Verfahren nach Anspruch 1, bei dem die Dehydrierungsreaktion im Schritt (a) ausgeführt wird bei einer Temperatur im Bereich von 450 bis 650 °C bei atmosphärischem oder leicht höherem Druck mit einer GHSV-Raumgeschwindigkeit im Bereich von 100 bis 1.000 h⁻¹ und mit einer Verweilzeit des Katalysators im Bereich von 5 bis 30 Minuten.

13. Verfahren nach Anspruch 12, bei dem die Raumgeschwindigkeit im Bereich von 150 bis 300 h⁻¹ und die Verweilzeit des Katalysators im Bereich von 10 bis 15 Minuten liegt.

14. Verfahren nach Anspruch 1, bei dem die Regenerierung des Katalysators im Schritt (b) mit Luft oder Sauerstoff ausgeführt wird, während seine Erwärmung ausgeführt wird unter Verwendung von Methan, einem Brenngas oder Nebenprodukten der Dehydrierungsreaktion, wobei mit einer höheren Temperatur in Bezug auf die durchschnittliche Dehydrierungstemperatur bei atmosphärischem oder leicht höherem Druck mit einer Raumgeschwindigkeit im Bereich von 100 bis 1.000 h⁻¹ und mit einer Verweilzeit des Katalysators von 5 bis 60 Minuten gearbeitet wird.

15. Verfahren nach Anspruch 1, bei dem im Schritt a) das inerte Gas ein Gasstrom ist, der im wesentlichen aus von den Verbrennungsböden des Regenerators zurückgewonnenem Stickstoff besteht.

16. Verfahren nach Anspruch 1, bei dem im Schritt a) das Ethylbenzol in den Reaktor gemischt mit Paraffin, ausgewählt aus Ethan, Propan oder Isobutan, eingeführt wird, wobei man die gleichzeitige Dehydrierung der Komponenten des Gemisches derart erhält, so daß sich Styrol bzw. die entsprechenden Olefine ergeben.


18. Verfahren nach Anspruch 17, bei dem das Ethylen zu einer Alkylierungseinheit zusammen mit einem Strom von Benzol recyclert wird, so daß sich Ethylbenzol ergibt.

Revendications

1. Procédé de déshydrogénation d'éthylbenzène en styrène qui comprend les étapes consistant à :

   (a) mettre en réaction l'éthylbenzène mélangé avec un gaz inerte dans un réacteur à lit fluidisé, en présence d'un système catalytique constitué d'oxyde de fer et de promoteurs supportés sur de l'alumine modifiée avec
0,01 à 10% en poids de silice et fonctionnant à une température allant de 400 à 700°C, à une pression totale de 10,13 à 303,9 kPa (Pa abs.) (0,1 à 3 ata) et avec une vitesse spatiale GHSV allant de 60 à 10 000 h⁻¹ (litres normaux d'un mélange d'éthylbenzène et de gaz inerte /h x litre de catalyseur) ; et
(b) régénérer et chauffer le catalyseur dans un régénérateur à une température dépassant 400°C.

2. Procédé selon la revendication 1, dans lequel le catalyseur est constitué de :

(1) 1 à 60% en poids d'oxyde de fer ;
(2) 0,1 à 20% en poids d'au moins un oxyde de métal alcalin ou alcalino-terreux ;
(3) 0 à 15% en poids d'un second promoteur constitué d'au moins un oxyde terreux rare ;
(4) le complément jusqu'à 100 étant un support constitué d'une alumine microsphéroïdale choisie parmi celles en phase delta, thêta ou leurs mélanges, en phase thêta + alpha ou en phase delta + thêta + alpha, modifiée avec 0,08 à 5% en poids de silice.

3. Procédé selon la revendication 1 ou 2, dans lequel le catalyseur est constitué de :

(1) 5 à 50% en poids d'oxyde de fer ;
(2) 0,5 à 10% en poids d'un promoteur métallique, sous forme d'oxyde.
(3) le complément jusqu'à 100 étant un support constitué par une alumine microsphéroïdale ayant un diamètre allant de 60 à 70 microns choisie parmi celles en phase delta, thêta ou leurs mélanges, en phase thêta + alpha ou en phase delta + thêta + alpha, modifiée de préférence avec 0,08 à 3% en poids de silice.

4. Procédé selon l'une quelconque des revendications précédentes, dans lequel le promoteur est choisi parmi les métaux alcalins, les métaux alcalino-terreux ou dans le groupe des lanthanides.

5. Procédé selon la revendication 4, dans lequel le promoteur est un oxyde de potassium.

6. Procédé selon la revendication 4, dans lequel les promoteurs sont de l'oxyde de potassium, oxyde de cérium, oxyde de lantanum et oxyde de praséodyme.

7. Procédé selon l'une quelconque des revendications précédentes, dans lequel le catalyseur est obtenu par les étapes consistant à :

(a) ajouter une aliquote du promoteur au support ;
(b) effectuer un séchage de 100 à 150°C et, facultativement, calciner le solide séché à une température ne dépassant pas 900°C ;
(c) disperser l'oxyde de fer et l'aliquote restante du promoteur sur le support obtenu dans (a) ; et
(d) effectuer un séchage de 100 à 150°C et calciner le solide séché à une température allant de 500 à 900°C ;

et dans lequel les étapes (c) et (d) peuvent être répétées plusieurs fois.

8. Procédé selon la revendication 1, dans lequel le gaz inerte est choisi parmi l'azote, le méthane, l'hydrogène et la vapeur d'eau.

9. Procédé selon la revendication 8, dans lequel le gaz inerte est choisi parmi l'azote et le méthane.

10. Procédé selon la revendication 1, dans lequel le rapport volumétrique gaz inerte/éthylbenzène varie de 1 à 6.

11. Procédé selon la revendication 10, dans lequel le rapport volumétrique varie de 2 à 4.

12. Procédé selon la revendication 1, dans lequel la réaction de déshydrogénation dans l'étape (a) est réalisée à une température allant de 450 à 650°C, à une pression atmosphérique ou légèrement supérieure, à une vitesse spatiale GHSV allant de 100 à 1 000 h⁻¹ et avec un temps de séjour du catalyseur allant de 5 à 30 minutes.

13. Procédé selon la revendication 12, dans lequel la vitesse spatiale varie de 150 à 300 h⁻¹ et le temps de séjour du catalyseur varie de 10 à 15 minutes.

14. Procédé selon la revendication 1, dans lequel dans l'étape (b) la régénération du catalyseur est réalisée avec de
l'air ou de l'oxygène tandis que son chauffage est effectué en utilisant du méthane, un gaz combustible ou des sous-produits de la réaction de déshydrogénation, fonctionnant à une température plus élevée par rapport à la température moyenne de déshydrogénation, à une pression atmosphérique ou légèrement supérieure, à une vê-
locité spatiale allant de 100 à 1 000 h⁻¹ et avec un temps de séjour du catalyseur de 5 à 60 minutes.

15. Procédé selon la revendication 1, dans lequel dans l'étape (a) le gaz inerte est un flux gazeux essentiellement constitué d'azote récupéré des produits de combustion du régénérateur.

16. Procédé selon la revendication 1, dans lequel dans l'étape (a) l'éthylbenzène est amené dans le réacteur mélangé avec une paraffine choisie parmi l'éthane, le propane ou l'isobutane obtenant la déshydrogénation contemporaine des composants du mélange pour donner du styrène et les oléfines correspondantes, respectivement.

17. Procédé selon la revendication 16, dans lequel l'éthylbenzène est amené dans le réacteur mélangé avec de l'éthan-
ène obtenant la déshydrogénation contemporaine des composants du mélange pour donner du styrène et de l'éthy-
lène respectivement.

18. Procédé selon la revendication 17, dans lequel l'éthylène est recyclé vers une unité d'alkylation conjointement avec un flux de benzène pour donner de l'éthylbenzène.