

Use of titanium dioxide mixtures for producing catalysts

Description

5 The present invention relates to the use of titanium dioxide mixtures in the anatase form which have defined physical properties for producing catalysts which are suitable, in particular, for the synthesis of phthalic anhydride. The invention further relates to catalysts comprising titanium dioxide mixtures in the anatase form which have defined physical properties.

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Catalysts for preparing phthalic anhydride which comprise vanadium pentoxide and titanium dioxide have been known for a long time. Titanium dioxide in the anatase modification is the main constituent of the active composition of these phthalic anhydride catalysts and serves as support for the catalytically active and selective

15 vanadium pentoxide components.

DE-A 2 106 796 describes the production of supported catalysts for the oxidation of o-xylene to phthalic anhydride, in which the titanium dioxide has a BET surface area of from 15 to 100 m²/g, preferably from 25 to 50 m²/g. A mixture of anatase having a BET

20 surface area of from 7 to 11 m²/g and hydrated titanium dioxide having a BET surface area of > 100 m²/g is particularly suitable, while the components alone would not be suitable.

EP-A 522 871 describes a relationship between the BET surface area of the titanium dioxide and the catalyst activity. According to this document, the catalyst activity is low

25 when titanium dioxide having BET surface areas of less than 10 m²/g is used. When titanium dioxide having a BET surface area of greater than 60 m²/g is used, the life of the catalyst is reduced and the phthalic anhydride yield decreases sharply. Preference is given to BET surface areas of from 15 to 40 m²/g.

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To improve the phthalic anhydride yield and the starting behavior of the catalysts, a change has been made in recent years to the use of activity-structured catalysts. The individual catalyst zones are structured so that the activity of the individual zones generally increases from the reactor inlet to the reactor outlet.

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For example, EP-A 985 648 describes the preparation of phthalic anhydride by catalytic gas-phase oxidation of o-xylene and/or naphthalene using a catalyst system which is structured so that the porosity of the catalyst and thus the activity increases pseudocontinuously from the reactor inlet to the reactor outlet. The porosity is defined

40 as the free volume between the coated shaped bodies of the bed in the reaction tube. In the examples, the specific surface area of the active components was altered by

varying the specific surface area of the titanium dioxide, which was in the range from 40 to 140 m²/g.

According to the prior art summarized in EP-A1 063 222, the activity can be increased in very different ways:

- (1) by means of a continual increase in the phosphorus content,
- (2) by means of a continual increase in the content of active composition,
- (3) by means of a continual decrease in the alkali metal content,
- (4) by means of a continual decrease in the empty space between the individual catalysts,
- (5) by means of a continual decrease in the content of the inert materials or
- (6) by means of a continual increase in the temperature

from the upper zone (reactor inlet) to the bottom zone (reactor outlet).

The BET surface area of the titanium dioxide should be in the range from 10 to 60 m²/g. In the examples of EP-A1 063 222, the BET surface area is constant at 22 m²/g.

In multizone catalyst systems, the decrease in the activity of the first catalyst zone has an adverse effect on the life of the catalyst. With increasing aging, the conversion in the region of the first highly selective zone decreases. Over the course of the catalyst life, the main reaction zone migrates ever deeper into the catalyst bed, i.e. the o-xylene or naphthalene feed is to an increasing extent reacted only in the subsequent less selective zones. The consequences are reduced phthalic anhydride yields and an increased concentration of by-products or unreacted starting materials. To avoid migration of the main reaction zone into the subsequent zones, the salt bath temperature can be continually increased. However, as the period of operation of the catalysts increases, this measure, too, leads to a reduction in the phthalic anhydride yield.

It was therefore an object of the invention to provide catalysts having improved properties, especially in respect of the yield. In particular, oxidation catalysts, especially phthalic anhydride catalysts, having improved activity, selectivity and yield should be provided. A further object was to find oxidation catalysts which when used in an activity-structured multizone catalyst system combine the advantages of this with those of a long life and high selectivity of the first catalyst zones.

It has surprisingly been found that titanium dioxide(s) A in the anatase modification which has/have a BET surface area of greater than 15 m²/g and a hydrogen uptake for the reduction of Ti⁴⁺ to Ti³⁺ of from 5 to 20 μmol/m² in admixture with one or more further titanium dioxide(s) B in the anatase modification which has/have a BET surface

area of less than or equal to $15 \text{ m}^2/\text{g}$ and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 0.6 to $7 \text{ } \mu\text{mol}/\text{m}^2$ is/are particularly suitable for producing catalysts.

5 It is advantageous to use titanium dioxide(s) A having a BET surface area of from 18 to $90 \text{ m}^2/\text{g}$, in particular from 18 to $55 \text{ m}^2/\text{g}$. Titanium dioxide A preferably has a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 5 to $17 \text{ } \mu\text{mol}/\text{m}^2$.

10 It is advantageous to use titanium dioxide(s) B having a BET surface area of from 3 to $15 \text{ m}^2/\text{g}$. Titanium dioxide B preferably has a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 0.6 to $5 \text{ } \mu\text{mol}/\text{m}^2$.

The BET surface area of the titanium dioxide mixture of A and B is advantageously in the range from 5 to $50 \text{ m}^2/\text{g}$, in particular from 10 to $30 \text{ m}^2/\text{g}$.

15 The mixture advantageously has a ratio of titanium dioxide(s) A to titanium dioxides (B) of from $0.5:1$ to $6:1$, in particular from $1:1$ to $5:1$.

20 It is advantageous to mix no more than three titanium dioxides A and no more than three titanium dioxides B with one another. The titanium dioxide mixture used according to the invention particularly preferably comprises one titanium dioxide from each of the groups A and B.

25 In particular, the titanium dioxide mixture used according to the invention is suitable for producing catalysts which are used in an activity-structured, at least two-zone, preferably at least three-zone, catalyst system in the uppermost catalyst zone or in the upper catalyst zones, in particular in the uppermost catalyst zone, nearest the reactor inlet.

30 For the purposes of the present invention, an activity-structured catalyst system is a system comprising different catalyst zones, with the activity of the catalysts changing from one zone to the next zone. In general, preference is given to catalyst systems whose activity increases essentially continuously from the reactor inlet to the reactor outlet. However, it is also possible to use one or more catalyst zones which are located upstream or in intermediate positions and have a higher activity than the subsequent
35 zones.

When the titanium dioxide mixture used according to the invention is used in a multizone catalyst system, it is advantageous to employ a ratio of titanium dioxide(s) A to titanium dioxide(s) B of from $0.8:1$ to $3:1$, in particular from $1:1$ to $2.5:1$, in the
40 uppermost zone. Titanium dioxide mixtures or pure titanium dioxides in the anatase modification can be used in the further zones. When titanium dioxide mixtures are used, the ratio of A to B in the next lower zone is advantageously from $2:1$ to $5:1$.

The titanium dioxide mixture mentioned is particularly useful for producing oxidation catalysts for the synthesis of aldehydes, carboxylic acids and/or carboxylic anhydrides. In these catalytic gas-phase oxidations of aromatic or heteroaromatic hydrocarbons such as benzene, o-, m- or p-xylene, naphthalene, toluene, durene (1,2,4,5-tetramethylbenzene) or β -picoline (3-methylpyridine), products obtained are, for example, benzaldehyde, benzoic acid, maleic anhydride, phthalic anhydride, isophthalic acid, terephthalic acid, pyromellitic anhydride or nicotinic acid, depending on the starting material.

The titanium dioxide mixture mentioned is particularly useful for producing phthalic anhydride catalysts which are used in an activity-structured, at least two-zone, preferably at least three-zone, catalyst system in the uppermost catalyst zone (in a two-zone catalyst system), or in the two uppermost catalyst zones or in the uppermost catalyst zone (in a three-zone or multizone catalyst system). If appropriate, the upper catalyst zone according to the invention comprising the titanium dioxide mixture mentioned can be preceded by one or more catalyst zones.

Furthermore, it has been found that benzaldehyde, benzoic acid, maleic anhydride, phthalic anhydride, isophthalic acid, terephthalic acid, pyromellitic anhydride or nicotinic acid can be prepared advantageously using the novel catalyst described below. For this purpose, a mixture of a gas comprising molecular oxygen, for example air, and the starting material to be oxidized is generally passed through tubes in which a bed of the catalyst of the invention is located. The oxidation is particularly advantageously carried out using the catalyst of the invention in an activity-structured catalyst system.

Oxidic supported catalysts are suitable as catalysts. To prepare phthalic anhydride by gas-phase oxidation of o-xylene or naphthalene or mixtures thereof, use is usually made of spherical, annular or shell-like supports comprising a silicate, silicon carbide, porcelain, aluminum oxide, magnesium oxide, tin dioxide, rutile, aluminum silicate, magnesium silicate (steatite), zirconium silicate or cerium silicate or mixtures thereof. Coated catalysts in which the catalytically active composition has been applied in the form of a shell to the support have been found to be particularly useful. Vanadium pentoxide is preferably employed as catalytically active constituent. Furthermore, the catalytically active composition can further comprise small amounts of many other oxidic compounds which act as promoters to influence the activity and selectivity of the catalyst, for example by reducing or increasing its activity. Such promoters are, for example, the alkali metal oxides, thallium(I) oxide, aluminum oxide, zirconium oxide, iron oxide, nickel oxide, cobalt oxide, manganese oxide, tin oxide, silver oxide, copper oxide, chromium oxide, molybdenum oxide, tungsten oxide, iridium oxide, tantalum oxide, niobium oxide, arsenic oxide, antimony oxide, cerium oxide and phosphorus pentoxide. The alkali metal oxides act, for example, as promoters which reduce the

activity and increase the selectivity. Furthermore, organic binders, preferably copolymers, advantageously in the form of an aqueous dispersion, of vinyl acetate/vinyl laurate, vinyl acetate/acrylate, styrene/acrylate, vinyl acetate/maleate, vinyl acetate/ethylene, and also hydroxyethylcellulose can be added to the catalytically active composition. The amounts of binder used are from 3 to 20% by weight, based on the solids content of the solution of the constituents of the active composition (EP-A 744 214). Preference is given to using organic binders as described in DE-A 198 24 532. If the catalytically active composition is applied to the support without organic binders, coating temperatures above 150°C are advantageous. When the binders indicated above are added, usable coating temperatures are, depending on the binder used, in the range from 50 to 450°C (DE-A 2106796). The binders applied burn out within a short time after installation of the catalyst and start-up of the reactor. The addition of binder has the advantage that the active composition adheres well to the support, so that transport and installation of the catalyst are made easier.

The catalyst for the synthesis of phthalic anhydride advantageously comprises, on a porous and/or nonporous support material, from 5 to 15% by weight, based on the total catalyst, of active composition comprising from 3 to 30% by weight of V_2O_5 , from 0 to 4% by weight of Sb_2O_3 , from 0 to 1.0% by weight of P, from 0 to 1.5% by weight of alkali (calculated as alkali metal) and a mixture of titanium dioxide(s) A in the anatase modification which has/have a BET surface area of greater than 15 m²/g and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 5 to 20 $\mu\text{mol}/\text{m}^2$ and titanium dioxide(s) B in the anatase modification which has/have a BET surface area of less than or equal to 15 m²/g and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 0.6 to 7 $\mu\text{mol}/\text{m}^2$ as balance.

In a preferred embodiment, the catalyst in the first, uppermost zone comprises, on support material, from 5 to 12% by weight, based on the total catalyst, of active composition comprising from 3 to 20% by weight of V_2O_5 , from 0 to 4% by weight of Sb_2O_3 , from 0 to 0.5% by weight of P, from 0.1 to 1.5% by weight of alkali (calculated as alkali metal) and a mixture of titanium dioxide(s) A in the anatase modification which has/have a BET surface area of greater than 15 m²/g and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 5 to 20 $\mu\text{mol}/\text{m}^2$ and titanium dioxide(s) B in the anatase modification which has/have a BET surface area of less than or equal to 15 m²/g and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 0.6 to 7 $\mu\text{mol}/\text{m}^2$ as balance.

It is usual to employ multizone catalyst systems in which the less active catalyst is arranged in the fixed bed so that the reaction gas comes into contact with this catalyst first and only subsequently comes into contact with the more active catalyst in the second zone. If appropriate, catalyst zones which are located upstream or in intermediate positions and have a higher activity than the subsequent catalyst zone can be used. The reaction gas then comes into contact with the even more active

catalyst zones. The catalysts of differing activity can be thermostated to the same temperature or to different temperatures.

Preference is given to using three- to five-zone catalyst systems, in particular three- and four-zone catalyst systems. Particular preference is given to catalyst systems whose catalyst activity increases essentially continuously from zone to zone.

In a preferred embodiment of an at least three-zone catalyst system, the catalysts for the synthesis of phthalic anhydride have the following composition:

- for the first, uppermost zone (zone a) nearest the reactor inlet):
from 7 to 10% by weight, based on the total catalyst, of active composition comprising:
from 6 to 11% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0.1 to 1% by weight of an alkali (calculated as alkali metal), in particular cesium oxide,
and, as balance to 100% by weight, a mixture of titanium dioxide(s) A in the anatase modification which has/have a BET surface area of greater than $15 \text{ m}^2/\text{g}$ and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 5 to $20 \text{ } \mu\text{mol}/\text{m}^2$ and titanium dioxide(s) B in the anatase modification which has/have a BET surface area of less than or equal to $15 \text{ m}^2/\text{g}$ and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 0.6 to $7 \text{ } \mu\text{mol}/\text{m}^2$
- for the second, middle zone (zone b)):
from 7 to 12% by weight, based on the total catalyst, of active composition comprising:
from 5 to 13% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0 to 0.4% by weight of an alkali (calculated as alkali metal), in particular cesium oxide,
from 0 to 0.4% by weight of phosphorus pentoxide (calculated as P)
and, as balance to 100% by weight titanium dioxide in the anatase modification, if appropriate as in zone a)
- for the third, bottommost zone (zone c) nearest the reactor outlet):
from 8 to 12% by weight, based on the total catalyst, of active composition comprising:
from 5 to 30% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0 to 0.3% by weight an alkali (calculated as alkali metal), in particular cesium oxide

from 0.05 to 0.4% by weight of phosphorus pentoxide (calculated as P) and, as balance to 100% by weight titanium dioxide, in particular in the anatase modification, if appropriate as in zone a).

5 In a preferred embodiment of an at least four-zone catalyst system, the catalysts have the following composition:

- for the first zone (zone a) nearest the reactor inlet):
from 7 to 10% by weight, based on the total catalyst, of active composition
10 comprising:
from 6 to 11% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0.1 to 1% by weight of an alkali (calculated as alkali metal), in particular cesium oxide,
15 and, as balance to 100% by weight, a mixture of titanium dioxide(s) A in the anatase modification which has/have a BET surface area of greater than $15 \text{ m}^2/\text{g}$ and a hydrogen uptake for the reduction of Ti^{4+} to Ti^{3+} of from 5 to $20 \text{ } \mu\text{mol}/\text{m}^2$ and titanium dioxide(s) B in the anatase modification which has/have a BET surface area of less than or equal to $15 \text{ m}^2/\text{g}$ and a hydrogen uptake for the
20 reduction of Ti^{4+} to Ti^{3+} of from 0.6 to $7 \text{ } \mu\text{mol}/\text{m}^2$
- for the second zone (zone b1)):
from 7 to 12% by weight, based on the total catalyst, of active composition
comprising:
25 from 4 to 15% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0.1 to 1% by weight of an alkali (calculated as alkali metal), in particular cesium oxide
from 0 to 0.4% by weight of phosphorus pentoxide (calculated as P)
30 and, as balance to 100% by weight, titanium dioxide in the anatase modification, if appropriate as in zone a)
- for the third zone (zone b2)):
from 7 to 12% by weight, based on the total catalyst, of active composition
35 comprising:
from 5 to 15% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0 to 0.4% by weight of an alkali (calculated as alkali metal), in particular cesium oxide
40 from 0 to 0.4% by weight of phosphorus pentoxide (calculated as P)
and, as balance to 100% by weight, titanium dioxide in the anatase modification, if appropriate as in zone a)

- for the fourth zone (zone c) nearest the reactor outlet):
from 8 to 12% by weight, based on the total catalyst, of active composition comprising:
5 from 5 to 30% by weight of vanadium (calculated as V_2O_5)
from 0 to 3% by weight of antimony trioxide
from 0.05 to 0.4% by weight of phosphorus pentoxide (calculated as P)
and, as balance to 100% by weight, titanium dioxide in the anatase modification, if appropriate as in zone a).

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In general, the catalyst zones a), b1), b2) and/or c) can also each consist of two or more zones. These intermediate zones advantageously have intermediate catalyst compositions.

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Instead of mutually delineated zones of the various catalysts, it is also possible for a pseudocontinuous transition of the zones and an effectively uniform increase in the activity to be obtained by provision of a zone comprising a mixture of the successive catalysts at the transition from one zone to the next zone.

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To carry out the reaction, the catalysts are introduced zonewise into the tubes of a shell-and-tube reactor. The reaction gas is passed over the catalyst bed obtained in this way at salt bath temperatures of generally from 300 to 450°C, preferably from 320 to 420°C and particularly preferably from 340 to 400°C. The various catalyst beds can, however, also be thermostated to different temperatures.

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The bed length of the first catalyst zone preferably makes up from > 20 to 80% of the total catalyst fill height in the reactor. The bed height of the first two or the first three catalyst zones advantageously makes up from > 60 to 95% of the total catalyst fill height. If appropriate, one or more catalyst zones which preferably make up less than
30 20% of the total catalyst fill height can be located upstream of the abovementioned first catalyst zone. Typical reactors have a fill height of from 250 cm to 350 cm. The catalyst zones can also, if appropriate, be distributed over a plurality of reactors.

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The reaction gas fed to the catalyst (starting gas mixture) is generally produced by
35 mixing a gas which comprises molecular oxygen and can further comprise, in addition to oxygen, suitable reaction moderators such as nitrogen and/or diluents such as steam and/or carbon dioxide with the o-xylene or naphthalene to be oxidized. The reaction gas generally comprises from 1 to 100 mol%, preferably from 2 to 50 mol% and particularly preferably from 10 to 30 mol%, of oxygen. In general, the reaction gas
40 is laden with from 5 to 140 g, preferably from 60 to 120 g and particularly preferably from 80 to 120 g, of o-xylene and/or naphthalene per standard m³ of gas.

If desired, a downstream finishing reactor as described, for example, in DE-A 198 07 018 or DE-A 20 05 969 can also be provided for the preparation of phthalic anhydride. The catalyst used here is preferably a catalyst which is even more active than the catalyst of the last zone.

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The catalysts of the invention have the advantage of improved performance. This improvement is also found at high loadings with o-xylene and/or naphthalene, e.g. 100 g/standard m³.

Examples

A. Production of the catalysts

5 A.1 Production of the catalyst system 1 according to the invention
(4-zone catalyst system)

Upper zone (a)

29.3 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 69.8 g of anatase
10 (BET SA: 20 m²/g, H₂ uptake: 7.7 μmol/m²), 7.8 g of V₂O₅, 1.9 g of Sb₂O₃, 0.49 g of
Cs₂CO₃ were suspended in 550 ml of deionized water and stirred for 18 hours. 50 g of
organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a
50% strength by weight aqueous dispersion were added to this suspension. The
suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium
15 silicate) in the form of rings having an external diameter of 7 mm, a length of 7 mm and
a wall thickness of 1.5 mm and dried. The weight of the shell applied was 8% of the
total weight of the finished catalyst.

The catalytically active composition applied in this way comprised 7.1% by weight of
vanadium (calculated as V₂O₅), 1.8% by weight of antimony (calculated as Sb₂O₃),
20 0.36% by weight of cesium (calculated as Cs) after calcination at 450°C for one hour.
The BET surface area of the TiO₂ mixture was 15.8 m²/g.

Upper middle zone (b1)

24.6 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 74.5 g of anatase
25 (BET SA: 20 m²/g, H₂ uptake: 7.7 μmol/m²), 7.8 g of V₂O₅, 2.6 g of Sb₂O₃, 0.35 g of
Cs₂CO₃ were suspended in 550 ml of deionized water and stirred for 18 hours. 50 g of
organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a
50% strength by weight aqueous dispersion were added to this suspension. The
suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium
30 silicate) in the form of rings having an external diameter of 7 mm, a length of 7 mm and
a wall thickness of 1.5 mm and dried. The weight of the shell applied was 8% of the
total weight of the finished catalyst.

The catalytically active composition applied in this way, i.e. the catalyst shell,
comprised 7.1% by weight of vanadium (calculated as V₂O₅), 2.4% by weight of
antimony (calculated as Sb₂O₃), 0.26% by weight of cesium (calculated as Cs) after
35 calcination at 450°C for one hour. The BET surface area of the TiO₂ mixture was
16.4 m²/g.

Lower middle zone (b2)

40 24.8 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 74.5 g of anatase
(BET SA: 20 m²/g, H₂ uptake: 7.7 μmol/m²), 7.8 g of V₂O₅, 2.6 g of Sb₂O₃, 0.13 g of
Cs₂CO₃ were suspended in 550 ml of deionized water and stirred for 18 hours. 50 g of

organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a 50% strength by weight aqueous dispersion were added to this suspension. The suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium silicate) in the form of rings having an external diameter of 7 mm, a length of 7 mm and a wall thickness of 1.5 mm and dried. The weight of the shell applied was 8% of the total weight of the finished catalyst.

The catalytically active composition applied in this way, i.e. the catalyst shell, comprised 7.1% by weight of vanadium (calculated as V_2O_5), 2.4% by weight of antimony (calculated as Sb_2O_3), 0.10% by weight of cesium (calculated as Cs) after calcination at 450°C for one hour. The BET surface area of the TiO_2 mixture was 16.4 m²/g.

Bottom zone (c)

17.2 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 69.1 g of anatase (BET SA: 27 m²/g, H₂ uptake: 16.1 μmol/m²), 21.9 g of V_2O_5 , 1.5 g of $NH_4H_2PO_4$ were suspended in 550 ml of deionized water and stirred for 18 hours. 55 g of organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a 50% strength by weight aqueous dispersion were added to this suspension. The suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium silicate) in the form of rings having an external diameter of 7 mm, a length of 7 mm and a wall thickness of 1.5 mm and dried. The weight of the shell applied was 8% of the total weight of the finished catalyst.

The catalytically active composition applied in this way, i.e. the catalyst shell, comprised 20.00% by weight of vanadium (calculated as V_2O_5), 0.38% by weight of phosphorus (calculated as P) after calcination at 450°C for one hour. The BET surface area of the TiO_2 mixture was 20.9 m²/g.

A.2 Production of the catalyst system 2 according to the invention (3-zone catalyst system)

Upper zone (a)

34.3 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 63.6 g of anatase (BET SA: 20 m²/g, H₂ uptake: 7.7 μmol/m²), 7.74 g of V_2O_5 , 2.58 g of Sb_2O_3 , 0.48 g of Cs_2CO_3 were suspended in 650 ml of deionized water and stirred for 15 hours. 50 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 8% of the total weight of the finished catalyst.

The catalytically active composition applied in this way comprised 7.1% by weight of V_2O_5 , 2.4% by weight of Sb_2O_3 , 0.36% by weight of Cs after calcination at 400°C for 4 hours. The BET surface area was 14.7 m²/g.

Middle zone (b)

24.6 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 54.9 g of anatase (BET SA: 27 m²/g, H₂ uptake: 16.1 μmol/m²), 7.74 g of V₂O₅, 2.37 g of Sb₂O₃, 0.10 g of Cs₂CO₃ were suspended in 650 ml of deionized water and stirred for 15 hours. 55 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 9% of the total weight of the finished catalyst. The catalytically active composition applied in this way comprised 8.6% by weight of V₂O₅, 2.6% by weight of Sb₂O₃, 0.10% by weight of Cs after calcination at 400°C for 4 hours. The BET surface area was 20.8 m²/g.

15 Bottom zone (c)

24.6 g of anatase (BET SA: 7 m²/g, H₂ uptake: 4.9 μmol/m²), 73.7 g of anatase (BET SA: 30 m²/g, H₂ uptake: 2.8 μmol/m²), 25.0 g of V₂O₅, 1.7 g of NH₄H₂PO₄ were suspended in 650 ml of deionized water and stirred for 15 hours. 62 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 10% of the total weight of the finished catalyst. The catalytically active composition applied in this way comprised 20.0% by weight of V₂O₅, 0.4% by weight of P after calcination at 400°C for 4 hours. The BET surface area was 24.2 m²/g.

A.3 Production of the comparative catalyst system 3 (3-zone catalyst system)

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Upper zone (a)

46.0 g of anatase (BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 51.9 g of anatase (BET SA: 27 m²/g, H₂ uptake: 16.1 μmol/m²), 7.74 g of V₂O₅, 2.58 g of Sb₂O₃, 0.44 g of Cs₂CO₃ were suspended in 650 ml of deionized water and stirred for 15 hours. 50 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, external diameter (ED) x length (L) x internal diameter (ID)) by spraying. The weight of the shell of active composition applied was 8% of the total weight of the finished catalyst.

The catalytically active composition applied in this way comprised 7.1% by weight of V_2O_5 , 2.4% by weight of Sb_2O_3 , 0.33% by weight of Cs after calcination at 400°C for 4 hours. The BET surface area was 18.4 m²/g.

5 Middle zone (b)

21.5 g of anatase (BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 86.1 g of anatase (BET SA: 27 m²/g, H₂ uptake: 16.1 μmol/m²), 14.2 g of V_2O_5 , 1.7 g of $NH_4H_2PO_4$ were suspended in 550 ml of deionized water and stirred for 15 hours. 55 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 9% of the total weight of the finished catalyst.

15 The catalytically active composition applied in this way comprised 11.5% by weight of V_2O_5 , 0.4% by weight of P after calcination at 400°C for 4 hours. The BET surface area was 21.3 m²/g.

Bottom zone (c)

20 24.6 g of anatase (BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 73.7 g of anatase (BET SA: 30 m²/g, H₂ uptake: 2.8 μmol/m²), 25.0 g of V_2O_5 , 1.7 g of $NH_4H_2PO_4$ were suspended in 550 ml of deionized water and stirred for 15 hours. 62 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 9% of the total weight of the finished catalyst.

The catalytically active composition applied in this way comprised 20.0% by weight of V_2O_5 , 0.4% by weight of P after calcination at 400°C for 4 hours. The BET surface area was 19.9 m²/g.

30

A.4 Production of the comparative catalyst system 4 (3-zone catalyst system)

Upper zone (a)

35 34.3 g of anatase (BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 63.6 g of anatase (BET SA: 20 m²/g, H₂ uptake: 1.5 μmol/m²), 7.74 g of V_2O_5 , 2.58 g of Sb_2O_3 , 0.48 g of Cs_2CO_3 were suspended in 650 ml of deionized water and stirred for 15 hours. 50 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 40 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 8% of the total weight of the finished catalyst.

The catalytically active composition applied in this way comprised 7.1% by weight of V_2O_5 , 2.4% by weight of Sb_2O_3 , 0.36% by weight of Cs after calcination at 400°C for 4 hours. The BET surface area was 16.1 m²/g.

5 Middle zone (b)

34.3 g of anatase (BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 102.9 g of anatase (BET SA: 20 m²/g, H₂ uptake: 1.5 μmol/m²), 11.0 g of V_2O_5 , 3.7 g of Sb_2O_3 , 2.3 g of $NH_4H_2PO_4$ and 0.19 g of Cs_2CO_3 were suspended in 650 ml of deionized water and stirred for 15 hours. 52 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 9% of the total weight of the finished catalyst.

10 The catalytically active composition applied in this way comprised 7.1% by weight of V_2O_5 , 2.4% by weight of Sb_2O_3 , 0.10% by weight of Cs, 0.4% by weight of P after calcination at 400°C for 4 hours. The BET surface area was 17.3 m²/g.

Bottom zone (c)

28.7 g of anatase (BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 86.2 g of anatase (BET SA: 30 m²/g, H₂ uptake: 2.8 μmol/m²), 29.2 g of V_2O_5 , 2.0 g of $NH_4H_2PO_4$ were suspended in 650 ml of deionized water and stirred for 15 hours. 60 g of an aqueous dispersion (50% by weight) of vinyl acetate and vinyl laurate were subsequently added to this suspension. The suspension was subsequently applied to 1200 g of shaped steatite bodies (magnesium silicate) in the form of rings (7 x 7 x 4 mm, ED x L x ID) by spraying. The weight of the shell of active composition applied was 10% of the total weight of the finished catalyst.

25 The catalytically active composition applied in this way comprised 20.0% by weight of V_2O_5 , 0.4% by weight of P after calcination at 400°C for 4 hours. The BET surface area was 24.8 m²/g.

30 A.5 Production of the comparative catalyst system 5 as described in WO 2004/103944 (catalyst 2) (4-zone catalyst system)

35 Upper zone (1)

29.27 g of anatase (TiO₂-1, BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 69.80 g of anatase (TiO₂-2, BET SA: 20 m²/g, H₂ uptake: 1.5 μmol/m²), 7.83 g of vanadium pentoxide, 2.61 g of antimony oxide, 0.49 g of cesium carbonate were suspended in 650 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion.

40 50 g of organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a 50% strength by weight aqueous dispersion were added to this suspension. The resulting suspension was subsequently sprayed onto 1200 g of steatite

(magnesium silicate) in the form of rings ($7 \times 7 \times 4$ mm, (ED) $\times$ (L) $\times$ (ID)) and dried. The weight of the shell applied was 8% of the total weight of the finished catalyst. The catalytically active composition applied in this way, i.e. the catalyst shell, comprised 7.12% by weight of vanadium (calculated as V_2O_5), 2.37% by weight of antimony (calculated as Sb_2O_3), 0.36% by weight of cesium (calculated as Cs), 27.20% by weight of titanium dioxide (TiO_2 -1) and 63.46% by weight of titanium dioxide (TiO_2 -2) after calcination at 450°C for one hour.

Middle zone (b1)

24.61 g of anatase (TiO_2 -1, BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 74.46 g of anatase (TiO_2 -2, BET SA: 20 m²/g, H₂ uptake: 1.5 μmol/m²), 7.82 g of vanadium pentoxide, 2.60 g of antimony oxide, 0.35 g of cesium carbonate were suspended in 650 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. 50 g of organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a 50% strength by weight aqueous dispersion were added to this suspension. The suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium silicate) in the form of rings ($7 \times 7 \times 4$ mm, (ED) $\times$ (L) $\times$ (ID)) and dried. The weight of the shell applied was 8% of the total weight of the finished catalyst. The catalytically active composition applied in this way, i.e. the catalyst shell, comprised 7.12% by weight of vanadium (calculated as V_2O_5), 2.37% by weight of antimony (calculated as Sb_2O_3), 0.26% by weight of cesium (calculated as Cs), 22.60% by weight of titanium dioxide (TiO_2 -1) and 67.79% by weight of titanium dioxide (TiO_2 -2) after calcination at 450°C for one hour.

Middle zone (b2)

24.82 g of anatase (TiO_2 -1, BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 74.46 g of anatase (TiO_2 -2, BET SA: 20 m²/g, H₂ uptake: 1.5 μmol/m²), 7.82 g of vanadium pentoxide, 2.60 g of antimony oxide, 0.135 g of cesium carbonate were suspended in 650 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. 50 g of organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a 50% strength by weight aqueous dispersion were added to this suspension. The suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium silicate) in the form of rings ($7 \times 7 \times 4$ mm, (ED) $\times$ (L) $\times$ (ID)) and dried. The weight of the shell applied was 8% of the total weight of the finished catalyst. The catalytically active composition applied in this way, i.e. the catalyst shell, comprised 7.12% by weight of vanadium (calculated as V_2O_5), 2.37% by weight of antimony (calculated as Sb_2O_3), 0.10% by weight of cesium (calculated as Cs), 22.60% by weight of titanium dioxide (TiO_2 -1) and 67.79% by weight of titanium dioxide (TiO_2 -2) after calcination at 450°C for one hour.

Bottom zone (c)

17.23 g of anatase (TiO₂-1, BET SA: 9 m²/g, H₂ uptake: 0.4 μmol/m²), 69.09 g of anatase (TiO₂-3, BET SA: 27 m²/g, H₂ uptake: 2.8 μmol/m²), 21.97 g of vanadium pentoxide, 1.55 g of ammonium dihydrogen phosphate were suspended in 650 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. 50 g of organic binder comprising a copolymer of vinyl acetate and vinyl laurate in the form of a 50% strength by weight aqueous dispersion were added to this suspension. The suspension obtained was subsequently sprayed onto 1200 g of steatite (magnesium silicate) in the form of rings (7 × 7 × 4 mm, (ED) × (L) × (ID)) and dried. The weight of the shell applied was 8% of the total weight of the finished catalyst. The catalytically active composition applied in this way, i.e. the catalyst shell, comprised 20.0% by weight of vanadium (calculated as V₂O₅), 0.38% by weight of phosphorus (calculated as P), 15.73% by weight of titanium dioxide (TiO₂-1) and 62.90% by weight of titanium dioxide (TiO₂-3) after calcination at 450°C for one hour.

B Measurement of the hydrogen consumption in the reduction of Ti⁴⁺ to Ti³⁺

200 mg of the TiO₂ in the anatase modification were positioned as a powder bed in the reactor. A pretreatment to remove adsorbed water was carried out first. For this purpose, the sample was heated in helium at 20 K/min to 673 K and maintained at this temperature for one hour. After cooling to below 232 K and flushing with helium, the experiment was carried out. The sample was, for this purpose, heated at a ramp of 15 K/min to a final temperature of 1373 K in a stream of H₂/He (10% of H₂ in He, flow: 30 standard ml/min). The hydrogen consumption was determined by means of gas chromatography (thermal conductivity detector) and subsequently normalized to the amount used/surface area of the sample.

C Oxidation of o-xylene to phthalic anhydride

C.1 3-zone catalyst

From the bottom upward, 0.70 m of the catalyst of the bottom zone (c), 0.60 m of the catalyst of the middle zone (b) and 1.50 m of the catalyst of the upper zone (a) were introduced into an iron tube having a length of 3.85 m and an internal diameter of 25 mm. To regulate the temperature, the iron tube was surrounded by a salt melt, and a 2 mm thermocouple sheath having an installed withdrawable element was provided for measurement of the catalyst temperature. 4 standard m³/h of air laden with from 0 to 100 g/standard m³ of 98.5% strength by weight o-xylene were passed through the tube from the top downward. At 60-100 g of o-xylene/standard m³, the results summarized in table 2 were obtained ("PA yield" is the amount of PA obtained in percent by weight, based on 100% pure o-xylene).

C.2 4-zone catalyst

From the bottom upward, 0.70 m of the catalyst of the bottom zone (c), 0.70 m of the catalyst of the middle zone 2 (b2), 0.50 m of the catalyst of the middle zone 1 (b1) and
5 1.30 m of the catalyst of the upper zone (a) were introduced into an iron tube having a length of 3.85 m and an internal diameter of 25 mm. Otherwise, the experiment was carried out as indicated in C.1.

The experimental results after activation are summarized in table 1.

10 The following abbreviations were used:

	HST	Hot Spot Temperature
	UZ	Upper Zone
	SBT	Salt Bath Temperature
15	PHD	Phthalide
	PA	Phthalic Anhydride

Table 1: Results of the catalytic tests of the 4-zone catalysts

	Catalyst system 1	Catalyst system 1	Comparative catalyst system 5
Bed lengths [cm]	130, 50, 70, 70	130, 50, 70, 70	130, 50, 70, 70
o-Xylene loading [g/standard m ³]	80	100	100
SBT [°C]	365	362	360
HST UZ [°C]	439	447	440
PHD [% by weight]	0.03	0.03	0.02
PA yield [% by weight]	114.6	114.1	113.5

5 Table 2: Results of the catalytic tests of the 3-zone catalysts

	Catalyst system 2	Comparative catalyst system 3	Comparative catalyst system 4
Bed lengths [cm]	150, 70, 60	150, 60, 70	140, 80, 60
o-Xylene loading [g/standard m ³]	70	70	60
SBT [°C]	360	356	375
HST UZ [°C]	438	461	433
PHD [% by weight]	0.02	0.03	0.05
PA yield [% by weight]	113.5	111.5	112

Claims

1. The use of one or more titanium dioxide(s) A in the anatase modification which has/have a BET surface area of greater than 15 m²/g and a hydrogen uptake for the reduction of Ti⁴⁺ to Ti³⁺ of from 5 to 20 μmol/m² in admixture with one or more further titanium dioxide(s) B in the anatase modification which has/have a BET surface area of less than or equal to 15 m²/g and a hydrogen uptake for the reduction of Ti⁴⁺ to Ti³⁺ of from 0.6 to 7 μmol/m² for producing catalysts.
2. The use according to claim 1, wherein A has a BET surface area of from 18 to 90 m²/g.
3. The use according to claim 1, wherein A has a hydrogen uptake for the reduction of Ti⁴⁺ to Ti³⁺ of from 5 to 17 μmol/m².
4. The use according to claim 1, wherein B has a BET surface area of from 3 to 15 m²/g.
5. The use according to claim 1, wherein B has a hydrogen uptake for the reduction of Ti⁴⁺ to Ti³⁺ of from 0.6 to 5 μmol/m².
6. The use according to claim 1, wherein titanium dioxide(s) A and titanium dioxide(s) B are used in a ratio of from 0.5:1 to 6:1.
7. The use of titanium dioxide mixtures according to any of claims 1 to 6 for producing oxidation catalysts for the synthesis of aldehydes, carboxylic acids and/or carboxylic anhydrides.
8. The use of titanium dioxide mixtures according to any of claims 1 to 6 for producing oxidation catalysts for the synthesis of phthalic anhydride.
9. The use of titanium dioxide mixtures according to any of claims 1 to 6 for producing catalysts which are present in the upper zone of an activity-structured catalyst system.
10. A catalyst for preparing phthalic anhydride which comprises, on support material, from 5 to 15% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 3 to 30% by weight of V₂O₅, from 0 to 4% by weight of Sb₂O₃, from 0 to 1.0% by weight of P, from 0 to 1.5% by weight of alkali (calculated as alkali metal) and titanium dioxide mixtures according to any of claims 1 to 6 as balance.

11. A catalyst system comprising at least two superposed catalyst zones, wherein a catalyst according to claim 10 is used in the upper zone.

12. The catalyst system according to claim 11, comprising at least three superposed zones, wherein

a) the catalyst of the upper zone nearest the reactor inlet comprises, on support material, from 7 to 10% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 6 to 11% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0.1 to 1% by weight of alkali (calculated as alkali metal) and titanium dioxide mixtures according to any of claims 1 to 6 as balance,

b) the next lower active catalyst comprises, on support material, from 7 to 12% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 5 to 13% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0 to 0.4% by weight of P, from 0 to 0.4% by weight of alkali (calculated as alkali metal) and titanium dioxide in the anatase form, if appropriate as in zone a), as balance,

c) the next lower catalyst nearest the reactor outlet comprises, on support material, from 8 to 12% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 5 to 30% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0.05 to 0.4% by weight of P, from 0 to 0.3% by weight of alkali (calculated as alkali metal) and titanium dioxide in anatase form, if appropriate as in zone a), as balance.

13. The catalyst system according to claim 11 comprising at least four superposed zones, wherein

a) the catalyst of the upper zone nearest the reactor inlet comprises, on support material, from 7 to 10% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 6 to 11% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0.1 to 1% by weight of alkali (calculated as alkali metal) and titanium dioxide mixtures according to any of claims 1 to 6 as balance,

b1) the next lower active catalyst comprises, on support material, from 7 to 12% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 4 to 15% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0.1 to 1% by weight of alkali (calculated as

alkali metal), from 0 to 0.4% by weight of P and titanium dioxide in the anatase form, if appropriate as in zone a), as balance,

5 b2) the next lower active catalyst comprises, on support material, from 7 to 12% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 5 to 15% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0 to 0.4% by weight of alkali (calculated as alkali metal), from 0 to 0.4% by weight of P and titanium dioxide in anatase form, if appropriate as in zone a), as balance,

10 c) the next lower catalyst nearest the reactor outlet comprises, on support material, from 8 to 12% by weight, based on the total catalyst, of active composition, wherein the active composition comprises from 5 to 30% by weight of V_2O_5 , from 0 to 3% by weight of Sb_2O_3 , from 0.05 to 0.4% by weight of P and titanium dioxide in anatase form, if appropriate as in zone a), as balance.

14. A process for preparing phthalic anhydride by gas-phase oxidation of xylene, naphthalene or mixtures thereof in a shell-and-tube reactor, wherein xylene, naphthalene or mixtures thereof and a gas comprising molecular oxygen are passed over a catalyst according to claim 10 or a catalyst system according to any of claims 11 to 13.