Microspheres are produced by cobalt gamma radiation initiated polymerization of a dilute aqueous vinyl pyridine solution. Addition of cross-linking agent provides higher surface area beads. Addition of monomers such as hydroxyethylmethacrylate acrylamide or methacrylamide increases hydrophilic properties and surface area of the beads. High surface area catalytic supports are formed in the presence of controlled pore glass substrate.

17 Claims, 3 Drawing Figures
Fig. 2.

Fig. 3.
POLYVINYL PYRIDINE MICROSPHERES

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 83-568 (72 Stat. 435; 42 USC 2457).

CROSS-REFERENCE TO RELATED APPLICATION

This application is a division of Ser. No. 780,007, filed Mar. 22, 1977 now U.S. Pat. No. 4,170,685 which in turn is a Continuation-in-Part of an application Ser. No. 671,058 filed Mar. 29, 1976 now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to polymeric microspheres, particularly vinyl pyridine microspheres, and to methods for making the microspheres.

2. Description of the Prior Art

It has not been possible so far to produce polyvinyl pyridine microspheres of selected size and high purity from emulsion polymerization systems and the particles tend to agglomerate. Furthermore, the recovered particles are contaminated with impurities from the polymerization system which renders them unsuitable for many uses. The particles are generally hydrophobic in character and have relatively low surface area.

SUMMARY OF THE INVENTION

Suspensions of polyvinyl pyridine microspheres having a selected uniform diameter below 100 microns and preferably from 100A to 100,000A are provided in accordance with the invention. The standard deviation of the diameter of the microspheres was found to be of the order of 3 to 10%. The surface area of the microspheres can be considerably varied and adhesiveness is lower providing unagglomerated particles. The microspheres have exceptional purity since the polymerization system is free of initiator and emulsifier.

The microspheres are produced by applying ionizing radiation, from a suitable cobalt gamma source, to a 45% solution of vinyl pyridine in aqueous media. The microspheres can be separated by freeze drying or centrifugation of the resulting microsphere suspension. The vinyl pyridine monomer has exceptional resistance to the high energy radiation. Thus, overdoses of radiation do not degrade the microspheres and the microspheres are useful in radiation environments such as a radiation barrier material.

Hydrophilic characteristics are provided by addition of a suitable unsaturated comonomer and surface area is varied by addition of cross-linking agent or comonomer. Solubility of the monomers can be increased by addition of a water-miscible solvent such as an alkanol, suitably methanol or a ketone such as acetone. Optionally a small amount of stabilizer may be present.

Substrates, especially those having electronegative surfaces can be coated by applying the suspension of microspheres to the surface and removing the liquid. Quaternization of the nitrogens in the pyridine rings provide particles suitable for applications involving ion exchange. The modified particles can be used in the form of affinity chromatography columns for the separation of a variety of materials, specifically proteins, aldehydes and ketones. The high radiation resistance of the particles makes them suitable for application in nuclear technology and when quaternized with acids or halogen compounds, aqueous emulsions of the microspheres should find applications in biocidal preparations.

The high surface area films or microsphere agglomerates are useful as substrates for binding metal catalysts. The metal may be in the form of fine particles encapsulated in the microspheres by conducting the polymerization in presence of finely divided metal as disclosed in copending application Ser. No. 694,151 filed June 9, 1976 now abandoned. The tertiary amine functionality of the pendant pyridine group may be utilized to bind catalytic metal salts. In copending application Ser. No. 718,103 filed Aug. 27, 1976, now U.S. Pat. No. 4,123,396, issued on Oct. 31, 1978, the microsphere is impregnated with a metal salt which is then reduced to form finely divided black metal particles formed in situ within the microsphere.

Photoactivated polymer supported catalysts are disclosed in Ser. No. 666,184 filed Mar. 12, 1976, now abandoned and in a continuation-in-part application, Ser. No. 764,402, filed Jan. 31, 1977 now U.S. Pat. No. 4,127,506, issued on Nov. 28, 1978. The catalysts are prepared by photoirradiation of polyvinyl pyridine microspheres in presence of low valent transition metals such as Rh(CO)4, Ru(CO)4 or CO2(CO)8. The catalysts are useful in addition reactions such as hydroformylation of olefins to aldehydes.

The addition reaction may be conducted in the presence or absence of light. The yield of addition product increase dramatically when the surface area is increased preferably by depositing the polymer on porous, inert, finely divided substrates such as glass beads having a diameter below 1000 microns, preferably 10 to 150 microns, and pores from 50 to 500 nm preferably no more than 150 nm. Catalytic activity for the photoactivated catalyst is also strongly dependent on the polymer-glass ratio and yields are maximized when the polymer-glass ratio is from 1 to 40% by weight, preferably from 5 to 20% by weight.

These and other features and attendant advantages of the invention will become apparent as the invention becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a series of graphs of water absorption isotherms at room temperature with water absorption (g H2O/g polymer) as ordinate and relative humidity (P/Po×10^-2) as abscissa. The circled numbers refer to the examples of Table II;

FIG. 2 is a graph of bead diameter in microns as ordinate vs monomer concentration as abscissa showing the effect of monomer concentration; and

FIG. 3 is a set of graphs of bead diameter in microns as ordinate vs volume % of cosolvent as abscissa showing the effect of acetone or methanol solvent on particle size.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The monomer mixture contains at least 20% by weight of vinyl pyridine, preferably at least 50% by weight, optimally about 70% to 80% by weight. The
remaining comonomers are soluble in the aqueous medium, compatible, unsaturated compounds capable of addition polymerization with vinyl pyridine. The comonomers preferably contain a hydrophilic group such as carboxyl, amino or hydroxyl. Mono-unsaturated comonomers are suitably selected from amino, carboxyl or hydroxyl substituted acrylic monomers. Exemplary comonomers are acrylamide (AM), methacrylamide (MAM), acrylic acid, methacrylic acid (MA), dimethylaminomethacrylate or hydroxyl-lower alkyl- or amino-lower-alkyl-acrylates such as those of the formula:

\[ \text{CH}_2 = \text{O} \quad R_1 - \text{C} = \text{C} - R_2 \]

where \( R_1 \) is hydrogen or lower alkyl of 1-8 carbon atoms, \( R_2 \) is alkylene of 1-12 carbon atoms, and \( Z \) is \(-\text{OH} \) or \( -\text{N}-R_3 \) or \( -\text{R}_4 \)

where \( R_3 \) or \( R_4 \) are individually selected from H, lower alkyl or lower alkoxy of 1-8 carbon atoms. 2-hydroxyethyl methacrylate (HEMA), 3-hydroxypropyl methacrylate and 2-aminoethoxy methacrylate are readily available commercially. Surface area and hydrophilicity increase with increasing concentration of comonomer or water soluble cross-linking agent.

Polyunsaturated compounds also provide higher surface area and hydrophilicity and additionally provide cross-linked beads which are more regular in shape and less likely to agglomerate. Polyunsaturated compounds, a diene or triene polyvinyl compound, compounds having low water solubility such as ethylene glycol dimethacrylate or trimethylol propane trimethacrylate reduce surface area and hydrophilicity. However, water soluble compounds such as \( \text{N,N-methylene-bis-acrylamide (BAM)} \) or hexahydro-1,3,5-triacyloyl-s-triazine increase surface area and hydrophilicity.

Vinyl pyridines suitable for use in the invention are 2-vinyl pyridine, 4-vinyl pyridine and 2-methyl-5-vinyl pyridine. 2-vinyl pyridine has, in general, been found to be unsuitable due to the presence of water miscible solvents permits increased water solubility of vinyl pyridine or comonomer mixtures 6-10% or more. Microspheres produced at 3% vinyl pyridine monomer concentration or less will have a diameter below 3500Å. Solubility of the vinyl pyridine is increased by the addition of a water-miscible solvent such as methanol. The polymerization rate is considerably decreased requiring irradiation of the solution for a longer period.

Examples of practice follow.

4- and 2-vinyl pyridine were polymerized with or without various cross-linking agents in presence of water using Co-60 gamma radiation. The polymer was obtained in the form of microspheres whose average diameter depended on the initial concentration of the monomer (Table I). It was found that presence of cross-linking agents made the beads less likely to agglomerate. Agglomeration and size of the beads were reduced on adding 0.4% polyethylene oxide having molecular weight of 200,000 to 6,000,000 to the solution before polymerization.

<table>
<thead>
<tr>
<th>Conc. 4-VP wt/wt</th>
<th>Wt by Wt Ratio of BAM</th>
<th>Conc. Wt by Wt</th>
<th>Size of Beads</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1:9</td>
<td>0.25</td>
<td>900Å</td>
</tr>
<tr>
<td>0.45</td>
<td>1:9</td>
<td>0.50</td>
<td>900Å</td>
</tr>
<tr>
<td>0.90</td>
<td>1:9</td>
<td>1.00</td>
<td>1300Å</td>
</tr>
<tr>
<td>1.35</td>
<td>1:9</td>
<td>1.50</td>
<td>1600Å</td>
</tr>
<tr>
<td>1.80</td>
<td>1:9</td>
<td>2.00</td>
<td>1600Å</td>
</tr>
<tr>
<td>2.25</td>
<td>1:9</td>
<td>2.50</td>
<td>1600Å</td>
</tr>
<tr>
<td>2.7</td>
<td>1:9</td>
<td>3.00</td>
<td>2500Å</td>
</tr>
</tbody>
</table>

*Vacuum distilled from solid KOH; polymerization carried out in degassed solution.

**BAM** = acrylamide

TABLE I

Similar results were obtained using ethylene glycol dimethacrylate in place of BAM except that the size of the beads was smaller. The polymers were centrifuged, washed in benzene and then the trapped water was removed by azeotropic distillation using benzene. They were then dried in vacuo for 24 hours, washed again in benzene and dried again for 24 hours to yield a white powder.
The bead size is seen to increase monotonically with decreasing molecular weight of PEO.

The effect of monomer concentration on particle size was studied by varying monomer concentration of a 90% 4-VP, 10% BAM monomer mixture from 3-5%. MeOH/water solvent containing 0.4% PEO. The radiation dose was 1.2 megardas from a Co-60 gamma source. The particle size increased up to 3 microns as shown in FIG. 2.

In these experiments a marked improvement of size distribution was obtained when the pH of the polymerization mixture was lowered from a pH of 9.7 to 7.2. At the pH of 7.2, the beads had a diameter of 1.2μ and the standard deviation was less than 4%.

The effect of solvent concentration on particle size was investigated by varying methanol and acetone concentration from 0 to 30 ml/100 ml H2O in a solution containing 3% total monomer (90% 4-VP; 10% BAM/100 ml) and 0.4% PEO irradiated with 1.2 megardas from a Co-60 gamma source. The results illustrated in FIG. 3 show an increase in diameter of the beads with increasing solvent concentration, larger beads being produced in acetone at the same solvent concentration.

4-VP beads with up to 50% by weight of hydrophilic comonomer were prepared. Polyhema beads disclosed in copending application Ser. No. 634,935, filed Nov. 24, 1975 entitled "Preparation of Small Bio-Compatible Microspheres", the disclosure of which is expressly incorporated herein by reference, have been shown to be very useful for the specific binding of protein conjugates such as antibody or antigen by the glutaraldehyde or carbodiimide coupling reactions. The polyhema beads are soft swellable hydrophilic beads. Vinyl pyridine copolymer beads produced according to this invention will be harder and more durable since the polymerization in aqueous media will result in the formation of a hard cross-linked hydrophobic vinyl pyridine core with the orientation to the exterior of the bead of the hydrophilic hydroxyl or amino groups from the comonomer.

Copolymer beads were prepared by irradiation of an aqueous solution containing 2% total monomer including 4-VP, hydrophilic HEMA or AM comonomer and BAM cross-linking agent and 0.4% PEO with 1.2 megardas of Co-60 gamma radiation. The results are shown in the following table:

<table>
<thead>
<tr>
<th>4-VP</th>
<th>HEMA</th>
<th>AM</th>
<th>MAM</th>
<th>BAM</th>
<th>Particle Size (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>0.18 μ</td>
</tr>
<tr>
<td>70%</td>
<td>20%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>0.15 μ</td>
</tr>
<tr>
<td>60%</td>
<td>30%</td>
<td>20%</td>
<td>10%</td>
<td>10%</td>
<td>0.18 μ</td>
</tr>
<tr>
<td>70%</td>
<td>10%</td>
<td>30%</td>
<td>10%</td>
<td>10%</td>
<td>0.19 μ</td>
</tr>
<tr>
<td>60%</td>
<td>10%</td>
<td>20%</td>
<td>10%</td>
<td>10%</td>
<td>0.15 μ</td>
</tr>
<tr>
<td>40%</td>
<td>10%</td>
<td>30%</td>
<td>10%</td>
<td>10%</td>
<td>0.15 μ</td>
</tr>
<tr>
<td>80%</td>
<td>10%</td>
<td>20%</td>
<td>10%</td>
<td>10%</td>
<td>0.17 μ</td>
</tr>
<tr>
<td>60%</td>
<td>30%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>0.18 μ</td>
</tr>
</tbody>
</table>

Discrete, unagglomerated, spherical beads of uniform diameter having a hydrophilic sheath were produced. 1000Å beads of the following composition; vinyl pyridine (60%) acrylamide (30%) BAM (10%) were tested for capability of binding to antibodies. It was found that this type of beads did not exhibit non-specific binding to living cells e.g. murine lymphocytes.
Rh-PVP-glass supported catalysts are synthesized for batch reactor runs according to the following procedure:

1 g of poly-2-vinylpyridine is dissolved in 50 ml benzene and then filtered to remove insoluble impurities. The solution is added dropwise to 250 ml diethyl ether which is vigorously stirred at the same time. The polymer precipitates. It is settled, filtered and then dried. It may be redissolved in benzene and reprecipitated in ether. After drying, it is weighed. Yield or purification averages 60-90%. 25 g of pure polymer is dissolved in benzene (10 ml) and 2.5 g of ordinary glass powder or of controlled pore glass (CPG) are added to the solution. The solvent is driven off slowly, with stirring. The mixture is then irradiated with light from a Hanovia 450 watt lamp filtered through water for 16 hours with stirring. The mixture is then added and the reactor is filled with H2/CO mixture (80:20 v/v) to 76 psig pressure. The reactor is nitrogen atoms on the surface of the beads. Fairly large fluorescent microspheres were observed in the fluorescent microscope.

The above batch runs were repeated varying the ratio of polymer to glass from 0 to 100%. The catalytic activity is strongly dependent on polymer-glass ratio for acid conditions are preferred to quaternize the pyridine groups. Furthermore, yield of addition product is higher when the polymer-glass ratio is optimally at about 10% by weight.

The vinyl pyridine microspheres are found to bind to dyes containing acidic groups such as sulfonic acid or carboxyl.

The hard, discreet PVP microspheres when bound to fluorescent dyes provide a brightly fluorescent dye-bearing adduct very useful as a calibration standard for fluorescent microscopy, cell selection and cell counting instruments. Representative fluorescent dyes are fluorescein isothiocyanate (FITC) and rhodamine isothiocyanate. The dye is usually added in an amount between 1 to 30% of the beads by weight and the excess removed.

The procedure of Example 7 was repeated substituting rhodamine isothiocyanate for FITC. High intensity red fluorescent microspheres were observed in the fluorescent microscope.

There is a need for a calibration standard to determine RNA or DNA content of fluorescent dye stained cells for automated cytology instruments. The PVP beads of the invention have been found to bind to RNA, DNA, viruses or bacteria which contain RNA and DNA to fluorescent dyes such as ethidium bromide. Acid conditions are preferred to quaternize the pyridine nitrogen atoms on the surface of the beads. Fairly large beads of the order of 1 to 10 microns may be utilized.

The vinyl pyridine microspheres are found to bind to dyes containing acidic groups such as sulfonic acid or carboxyl.

The hard, discreet PVP microspheres when bound to fluorescent dyes provide a brightly fluorescent dye-bearing adduct very useful as a calibration standard for fluorescent microscopy, cell selection and cell counting instruments. Representative fluorescent dyes are fluorescein isothiocyanate (FITC) and rhodamine isothiocyanate. The dye is usually added in an amount between 1 to 30% of the beads by weight and the excess removed.

**TABLE V**

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Diameter, Mesh</th>
<th>Pore Size, nm</th>
<th>Activity (Turnover number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-80</td>
<td>150</td>
<td>~1/HR/Rh4</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>120-135</td>
<td>very good, 1-10 times better</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>non-porous</td>
<td>polymer did not attach to substrate</td>
</tr>
</tbody>
</table>

The vinyl pyridine microspheres are found to bind to dyes containing acidic groups such as sulfonic acid or carboxyl.

The hard, discreet PVP microspheres when bound to fluorescent dyes provide a brightly fluorescent dye-bearing adduct very useful as a calibration standard for fluorescent microscopy, cell selection and cell counting instruments. Representative fluorescent dyes are fluorescein isothiocyanate (FITC) and rhodamine isothiocyanate. The dye is usually added in an amount between 1 to 30% of the beads by weight and the excess removed.
where $R_1$ is hydrogen or lower alkyl of 1-8 carbon atoms, $R_2$ is alkyrene of 1-12 carbon atoms and $Z$ is $-$OH or

$$R_3 - N - R_4$$

where $R_3$ or $R_4$ are individually selected from H, lower alkyl or lower alkoxy of 1-8 carbon atoms; and 5 to 30% of a water-soluble, addition copolymerizable cross-linking agent; and

irradiating the solution with high energy radiation in absence of a chemical catalyst in an amount sufficient to generate free radicals capable of addition polymerizing the monomer mixture to form discrete microspheres, at least 80% of which have a diameter from 100Å to 60 microns, have a surface area of at least $1 \text{ m}^2/g$ and consist essentially of the addition copolymerized monomer mixture.

2. A method according to claim 1 in which the solution contains no more than 3% monomer and the average diameter of the microspheres is from 100Å and 3500Å.

3. A method according to claim 1 in which the monomer concentration is no more than 35% by weight and in which the aqueous solvent further including up to 50% by weight of a water-miscible organic solvent for the monomer which is a non-solvent for the microspheres.

4. A method according to claim 3 in which the solvent is a lower alkanol containing 1-8 carbon atoms.

5. A method according to claim 1 further including the step of immersing a substrate in the solution and forming a film of agglomerated microspheres in situ on the surface of the substrate.

6. A method according to claim 5 in which the substrate is porous glass particles.

7. A method according to claim 6 in which the particles have a diameter below 1000 microns and a pore size from 50 nm to 500 nm.

8. A method according to claim 6 in which the ratio of polymer to glass on the polymer coated particles is from 1% to 40% by weight.

9. A method according to claim 1 in which the solution further includes from 0.05 to 5% by weight of a water-soluble suspending agent.

10. A method according to claim 9 in which the suspending agent is a polyether.

11. A method according to claim 1 in which the cross-linking agent is selected from N,N'-methylene-bis-acylamide or hexahydro-1,3,5-triacryloyl-s-triazine.

12. A method according to claim 1 in which the high energy radiation source in an amount of 0.5 to 4.0 megas is a cobalt gamma source.

13. A method according to claim 1 in which the polymerization step is conducted under oxygen excluding conditions.

14. A method according to claim 1 in which the pH of the solution of monomers is adjusted to a pH of 5 to 8.5.

15. A method according to claim 14 in which the pH is about 7.

16. A method according to claim 1 in which the vinyl pyridine is 4-vinyl pyridine and the cross-linking agent is N,N'-methylene-bis-acylamide.

17. A method according to claim 1, in which said microspheres include a hard, cross-linked, hydrophilic, vinyl pyridine copolymeric core and a hydrophilic, monounsaturated comonomer copolymeric sheath.