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Standard Test Method for Determining Pore Volume Distribution of Catalysts by Mercury Intrusion Porosimetry¹

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1. Scope

1.1 This test method covers the determination of the pore volume distributions of catalysts and catalyst supports by the method of mercury intrusion porosimetry. The range of apparent diameters of pores for which it is applicable is fixed by the operant pressure range of the testing instrument. This range is typically between apparent pore entrance diameters of about 100 and 0.003 μm (3 nm).

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific hazard information is given in Section 8.

2. Referenced Documents

2.1 *ASTM Standards:*²

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E456 Terminology Relating to Quality and Statistics

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *apparent pore diameter*—the diameter of a pore, assumed to be cylindrical, that is intruded at a pressure, P , and is calculated with Eq 1.

3.1.2 *interparticle pores*—those pores that occur between particles when they are packed together and that are intruded during the test.

¹ This test method is under the jurisdiction of ASTM Committee D32 on Catalysts and is the direct responsibility of Subcommittee D32.01 on Physical-Chemical Properties.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.3 *intraparticle pores*—those pores lying within the envelopes of the individual catalyst particles and that are intruded during the test.

3.1.4 *intruded pore volume*—the volume of mercury that is intruding into the pores during the test after this volume has been corrected, if necessary, per 13.3.2.

4. Summary of Test Method

4.1 When a liquid does not wet a porous solid it will not voluntarily enter the pores in the solid by capillary attraction. The nonwetting liquid (mercury in this test method) must be forced into the pores by the application of external pressure. The size of the pores that are intruded is inversely proportional to the applied pressure. When a cylindrical pore model is assumed, the relationship between pressure and size is:

$$d = \frac{-4\gamma(\cos\theta)}{P} \quad (1)$$

where:

d = apparent diameter of the pore being intruded,

γ = surface tension of the mercury,

θ = contact angle between the mercury and the solid, and

P = absolute pressure causing the intrusion.

4.2 The volume of the intruded pores is determined by measuring the volume of mercury that is forced into them at various pressures. A single-pore size distribution determination involves increasing the pressure, either continuously or stepwise, and recording the measured intruded volume.

5. Significance and Use

5.1 This test method is intended to determine the volume distribution of pores in catalysts with respect to the apparent diameter of the entrances to the pores. In general, both the size and volume of pores in a catalyst affect its performance. Thus, the pore volume distribution is useful in understanding a catalyst's performance and in specifying a catalyst that can be expected to perform in a desired manner.

6. Limitations

6.1 Mercury intrusion porosimetry, in common with many other test methods, is only capable of sensing pores that are open to the outside of a catalyst particle, and will not determine the volume of any pores that are completely enclosed by surrounding solid. Also, the test method will only determine

the volume of intrudable pores that have an apparent diameter corresponding to a pressure within the pressuring range of the testing instrument.

6.2 The intrusion process proceeds from the outside of a particle toward its center. Comparatively large, interior pores can exist that have smaller pores as the only means of access. The test method will incorrectly register the entire volume of these “ink-bottle” pores as having the apparent diameter of the smaller access pores.

6.3 In the penetrometer, interparticle pores can be created in addition to the intraparticle pores. (See Section 3 for terminology.) These interparticle pores will vary in size and volume depending on the size and shape of the catalyst particles and on the manner in which the particles are packed together in the test chamber. It is possible that some of the interparticle pores will have the same apparent diameter as some of the intraparticle pores. When this occurs, the test method cannot distinguish between them. Thus, the test method can yield an intruded pore volume distribution that is, in part, dependent upon the packing of multi-particle samples. However, many catalysts have intraparticle pores that are much smaller than the interparticle pores. This situation leads to a bimodal pore size distribution and the distinction between the two classes of pores can frequently be made.

6.4 Mercury intrusion can involve the application of high pressures on the sample. This may result in a temporary, or permanent, alteration in the pore geometry. Generally, catalysts are made from comparatively strong solids and are less subject to these alterations than some other materials. However, the possibility remains that the use of the test method may alter the natural pore volume distribution that it seeks to measure.

7. Apparatus

7.1 *Mercury Intrusion Porosimeter*, equipped with a sample holder capable of containing one or several catalyst particles. This holder is frequently called a penetrometer. The porosimeter shall have a means of surrounding the test specimen with mercury at a low pressure, a pressure generator to cause intrusion, pressure transducers capable of measuring the intruding pressure with an accuracy of at least $\pm 1\%$ throughout the range of pressures over which the pores of interest are being intruded, and a means of measuring the intruded volume with an accuracy of at least $\pm 1\text{ mm}^3$ ($\pm 10^{-3}\text{ cm}^3$).

7.2 *Vacuum Pump*, if not part of the porosimeter, to evacuate the sample holder.

7.3 *Analytical Balance* capable of measuring the sample’s mass with an accuracy of at least $\pm 0.1\%$. This usually means that the balance must be sensitive to $\pm 10^{-7}\text{ kg}$ ($\pm 0.1\text{ mg}$).

7.4 *Mercury*, with a purity equal to, or better than, double distilled.

8. Hazards

8.1 Samples that have been exposed to mercury are dangerous. Apply the precautions that follow:

8.1.1 Mercury is a hazardous substance that can cause illness and death. Mercury can also be absorbed through the skin; avoid direct contact.

8.1.2 Always store in closed containers to control its evaporation, and use it only in well-ventilated rooms.

8.1.3 Wash hands immediately after any operation involving mercury.

8.1.4 Exercise extreme care to avoid spilling mercury. Clean up any spills immediately using procedures recommended explicitly for mercury.

8.1.5 Recycling of waste mercury is recommended and to be conducted in accordance with local government hazardous waste regulations. Disposal of waste mercury and mercury contaminated materials should be performed as mandated by local government hazardous waste regulations.

9. Sampling

9.1 The sample from which test material will be drawn shall be representative of the catalyst. The actual amount of catalyst used in a test will depend on the sensitivity of the porosimeter and the porosity of the sample.

10. Conditioning

10.1 The ideal preconditioning for the test specimen is an outgassing procedure that removes all foreign substances from the pores and pore walls of the catalyst, but does not alter the solid catalyst in any way. If possible, the appropriate combination of heat and vacuum and the required time of conditioning shall be experimentally determined for the specific catalyst under test. This outgassing technique shall then be the one specified and used.

10.2 Where the procedure described in 10.1 is not practical, outgas the catalyst in a vacuum of at least 1.3 Pa (10 μmHg) at a temperature of 150°C for at least 8 h.

NOTE 1—The procedure in 10.2 is unlikely to alter the pore structure of a catalyst but can severely change the pore structure of many other materials.

11. Procedure

11.1 Outgas the test sample in accordance with 10.1 or 10.2.

11.2 Weigh the outgassed specimen and record this weight.

11.3 Place the outgassed catalyst in the penetrometer in accordance with the manufacturer’s instructions.

NOTE 2—Since, when performing the operations described in 11.2 and 11.3, the outgassed catalyst is exposed to the laboratory atmosphere and can reabsorb vapors, carry these operations out as rapidly as possible.

11.4 Place the penetrometer containing the sample in the appropriate chamber of the porosimeter, following the manufacturer’s instructions, and evacuate to a pressure of at least 1.3 Pa (10 μmHg).

11.5 Fill the penetrometer with mercury, in accordance with the manufacturer’s instructions, by pressuring to some suitably low pressure.

NOTE 3—The pressure required to fill the penetrometer with mercury is also capable of filling sufficiently large pores of both the inter- and intra-particle classes. Thus, the filling process can fill some pores with mercury and the volume distribution of these pores cannot subsequently be determined. This fact should be recognized and, where possible, select a filling pressure that will not intrude pores in the diameter range of subsequent interest.

11.6 Place the filled penetrometer in the pressure vessel of the porosimeter and prepare the instrument for pressurization and intrusion readings in accordance with the manufacturer’s instructions.

11.7 Raise the pressure, either continuously or step-wise, and record both the absolute pressure and the volume of intruded mercury until the maximum pressure of interest is reached.

NOTE 4—When raising the pressure incrementally, minimize the pressure drop during the pause. Certain modern instruments allow for an automatic repressurization to the target pressure when the pressure decreases. When samples with relatively narrow pore size distribution are analyzed, the extent of depressurization and repressurization may affect test method precision and the measured pore volume.

NOTE 5—When testing some materials, the time required to achieve intrusion equilibrium will not be the same at all pressures. Often, the equilibrium time is appreciably longer at pressures that cause an abrupt and large increase in intruded volume. Failure to record the equilibrium intrusion will result in some of the pore volume being incorrectly ascribed to smaller pore diameters. Assess the extent to which this may be a problem by conducting two tests, each at a different pressuring rate, and compare the results. Measure recorded intrusion values at, essentially, equilibrium.

NOTE 6—Use of Eq 1 requires the absolute pressure, P . With some instruments, it may not be possible to read the absolute pressure directly. In this case, record the gage pressure and calculate the absolute pressures subsequently.

NOTE 7—If incremental pressure steps are used, the choice of pressure intervals at which data are to be recorded will be specified by those directing the test or, left to the judgement of the operator. A minimum of 10 to 15 data points will be required to define the pore volume distribution. Frequently, 25 or more points are found to be helpful. In selecting these pressure points, a rough idea of the expected distribution is helpful, since the pressure intervals can be larger in regions where little or no intrusion occurs. The intervals should be smaller in regions where a large volume of intrusion occurs abruptly.

NOTE 8—It is not necessary to continue the process up to the maximum pressuring capability of the instrument if all of the pores of interest in a particular test have been intruded at a lesser pressure.

11.8 Upon completion of the pressuring cycle, reduce the pressure and disassemble and clean the instrument in accordance with the manufacturer's instructions.

12. Blank Test for Corrections

12.1 An intrusion test on a nonporous sample may be required to obtain values to use in correcting intrusion data for compressibilities and temperature changes.

12.2 Select a nonporous material for this test that has approximately the same compressibility and bulk volume as the catalyst sample that is to be tested.

12.3 Test the nonporous sample in exactly the same manner as outlined in Section 11. Raise the pressure in the same manner as used for the catalyst tests to ensure that temperature changes due to pressuring are the same.

12.4 The results of this blank test are a series of measured volume changes that can also be expected to occur, along with actual pore intrusion, during a test on a catalyst. They are used to correct the intruded volumes as discussed in 13.3.2.

12.5 The compressibilities of the various components in the system augment the measured intrusion values while the pressure-induced heating and consequent expansion of the system reduces the measured volumes. In a particular instrument, either one of these effects may be dominant. Hence, the results of the blank test may be either an apparent intrusion (compressibility dominant) or an expulsion of mercury (heating dominant).

12.5.1 If the blank results show apparent intrusion, they are to be subtracted from the values measured in the test on the catalyst.

12.5.2 If the blank results show a mercury expulsion, they are to be added to the volumes measured on the catalyst.

13. Calculations

13.1 Express the intruding pressures as absolute pressures prior to computing the corresponding pore diameters. If the recorded values are gage pressures, they must be converted to absolute pressures in accordance with the instrument manufacturer's instructions. If the instrument reads directly in absolute pressure, omit this step.

13.2 The absolute pressures are next converted to apparent intruded pore diameters with the equation in 4.1. This step requires that the surface tension and contact angle be known.

13.2.1 When double-distilled mercury is used, the value of the surface tension can generally be relied upon to be that reported in handbooks, for example, 0.484 N/m (484 d/cm) at 25°C. Small deviations from this value are not significant as the surface tension enters the equation as a linear term.

13.2.2 The contact angle enters the equation as its cosine, and it is more important to know the value of the angle accurately for the material under test. The contact angle of mercury has been measured on a variety of solids by several different techniques, and references to some of these measurements are given in Appendix X1 which also lists references for several methods of contact angle measurement that have been found useful (1-6).³ The ideal value for reducing the data is one that has been determined for the particular material under test. If this is impractical, the use of an assumed value is necessary. If mercury intrusion is being used for the comparison of similar materials for quality control purposes, then an assumed, or agreed upon, value is satisfactory. But, when different materials are being compared, the assumption of a single value for the contact angle can lead to errors.

13.3 The next step in the calculations is the correction of the intruded volume readings. The corrections fall into two categories: low-pressure corrections and high-pressure corrections.

13.3.1 A low-pressure correction, that accounts for the compression of air trapped during filling, can be applied as discussed in Ref (4). However, this correction should not be necessary if mercury filling is carried out as required in 11.4.

13.3.2 The high-pressure correction to the intruded volume readings represents a composite of several phenomena for example, the compression of the sample, penetrometer, and mercury, and the temperature changes that occur as a result of pressurization. Experimentally determine the value of this correction with the blank intrusion test performed in Section 12. Either add to or subtract the values found in the blank test from the intrusion volumes as discussed in 12.5.

13.4 The final calculation is the conversion of the corrected intruded volumes to a unit mass basis. Divide each corrected intrusion value by the sample mass.

³ The boldface numbers in parentheses refer to the list of references at the end of this standard.