DETERMINATION OF THE MEAN PARTICLE DIAMETER, PARTICLE DENSITY, AND FRACTION VOIDS OF OTTAWA SAND

by

Robert S. Luttrell

A Thesis Submitted for Partial
Fulfillment of the Requirements
for the
Degree of Bachelor of Science

in

CHEMICAL ENGINEERING

Approved:

In Charge of Investigation

Head of Major Department

Virginia Polytechnic Institute
Blacksburg, Virginia

1955

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

One of the most recent developments in the field of unit operations is fluidization. Fluidization was developed primarily because of its important application in the petroleum industry. Some of the principal applications of fluidization are in the cracking of petroleum, synthesis of alcohols and gasoline, pneumatic transport of solids, and drying, to mention just a few.

The literature pertaining to fluidization is qualitative even though considerable research has and is being done on fluo-solids, and the information available covers only limited operating conditions. Fluidization occurs when particles of solids are maintained in a dense turbulent state by means of a moving fluid, usually an inert gas carrier. The physical variables in fluidization are the characteristics of the retaining vessel, fluidizing medium, and the particles to be fluidized. The important characteristic of the retaining vessel is the diameter-to-length ratio, the greater this ratio the less is the tendency for slugging. The important factors in fluidization are the velocity, density, and viscosity of the fluid,

while the properties of the fluidized solid which are of importance are the size, shape, density, surface tension, and electrostatic charge of the solid.

The research conducted on fluidization has been concerned primarily with the principles of fluid flow, however many factors concerning the effects of particle size, vessel diameter, particle shape, surface tension, and the electro-static charge have not been fully developed. In addition, considerable research has been directed towards heat and mass transfer in fluidized beds.

The purpose of the investigation was to determine the mean particle diameter, particle density, and the fraction voids of Ottawa sand (20-to 30-mesh, 30-to 50-mesh, and 50-to 70-mesh) to be used in extended studies on fluidization.

II. LITERATURE REVIEW

Fluidization, as it is known today, was first developed by the mineral industry for use in mineral separations. For generations pneumatic transport of solids, which is an application of fluidization, has been utilized. However, in the last few years the petroleum industry has made remarkable progress in the field of fluidization. The use of finely powdered solids as catalysts was first successfully applied to large-scale commercial operation in 1942 for the cracking of petroleum. In two years time, 1944, the fluid catalytic-cracking process accounted for fifty per cent of the total catalytic-cracking capacity. Following World War II, two-thirds of the catalytic-cracking capacity built employed the "fluid process". Fluidization has been accepted as a new unit operation by the petroleum industry, yet much of the research that has been and is being performed has not been published. The following literature review includes information on fluidization divided into applications of the fluo-solids technique, fluidization terminology, principles of fluidization, and mathematical correlations needed.

Applications of the Fluo-Solids Technique

There are no dates available for tracing the history of the fluidization of solid particles by means of a moving fluid. For many years solids have been transferred through pipes by pneumatic conveyance(33), which is fluidization in combination with solids transportation. The "teeter condition"(33), which is the fluidization of solid particles in water for separating minerals on a basis of differing particle sizes, shapes, and specific gravities, as used by the mineral industry, was one of the places the mineral industry began using fluidization. Fluidization is involved in any separation operation(33) in which a suspended solid or liquid is caused to flow with and countercurrent to another fluid. Fluidization of particles has been known for some time, however only recently has fluidization been applied to chemical engineering unit operations and processes(24). It has taken fluidization only a very few years to become recognized as a generally accepted unit operation of chemical engineering.

Applications of Fluidization in Chemical Engineering. In the early part of 1942 the use of finely powdered solids as catalysts was first successfully applied to large-scale commercial operations in the cracking of petroleum[22]. The success of fluidization is based on the growth of fluid catalytic-cracking capacity from 40,000 barrels per day in 1942, to 1,000,000 barrels per day in 1948[22]. The principal method of catalytic cracking for the entire oil refining industry is today the fluid catalytic cracking process[6].

Fluidization has been successfully applied to many other fields, some of which are fluidization in hydrocarbon synthesis[22], coal gasification[14], reduction of ores[20], Fischer-Tropsch reactions[24] for synthetic gasoline manufacture, drying[24], the oxidation of various hydrocarbons such as naphthalene[33], and transport of a variety of solids[24].

Advantages of a Fluidized Bed. The wide and immediate acceptance of the fluidized-solids technique was due to the several unique characteristics of a fluidized system. Before discussing the advantages of a fluidized bed, the difference between a fixed bed and a fluidized bed should

be understood. Murphy[29] has defined a fluidized bed as a mass of solid particles which exhibits the liquied-like characteristics of mobility, hydrostatic pressure, and an observable upper free surface or boundary zone across which a marked change in concentration of particles occurs; whereas, a fixed bed is defined as a body of motionless particles supported by direct contact with each other and the retaining walls of the container.

The basic advantages of the fluidized-solids system are the ease with which the solids may be transported from vessel to vessel permitting the most efficient utilization of heat and the ready development of a continuous process, and the extreme turbulence of the solid-gas suspensions allowing excellent heat transfer to be achieved to and from the system[29]. The above characteristics make the use of fluidized solids particularly applicable to those processes in which large amounts of heat must be transferred and large amounts of solids must be treated, as in catalyst regeneration[22].

Fluidization Terminology

The terminology used by many of the investigators is often different and overlapping and probably will remain as a glossary which will establish some permanent nomenclature. In 1949 Murphy[29] presented a rather incomplete glossary for establishing a permanent nomenclature in the field of fluidization.

Fluidization. Patterson[30] defined fluidization as that unit operation in which a mass of solid particles, usually finely divided, is maintained by means of an upwardly moving gas stream in a turbulent, dense state. Murphy[29] and other investigators[35] have further divided fluidization into particulate and aggregative fluidization.

Fixed Bed. A fixed bed[29] is a body of motionless solid particles supported by direct contact with each other and the retaining walls.

Moving Bed. A moving bed[29] is a body in which the particles remain in direct contact and are substantially fixed in position with respect to each other, but move with respect to the retaining walls.

Fluidized Mass. A fluidized mass[29] of solid particles is one which exhibits the mobility and hydrostatic pressure characteristic of a fluid. This condition may be achieved by suspending the particles by means of a stream of gas or liquid rising past the particles.

Fluidized Bed. A fludized bed[29] is a mass of solid particles which exhibits the liquid-like characteristics of mobility, hydrostatic pressure, and an observable upper free surface or boundary across which a marked change in concentration or particles occurs. In a fluidized bed, the random motion of the particles increases with increasing velocity of the supporting medium.

Channeling. The establishment of flow paths in a bed of solid particles through which a disproportionate quantity of the introduced fluid passes is known as channeling[29]. Channeling is especially encountered in fixed beds.

Slugging. Slugging[29] is a condition in which pockets or bubbles of the supporting fluid grow to the diameter of the containing vessel, and the mass of the particles trapped between adjacent pockets moves upward in a piston-like fashion. This condition is usually limited to vessels of high length-to-diameter ratio.

Dense Phase and Dilute Phase. In connection with catalytic cracking, Leva et al[14] stated that the terms dense-phase and dilute-phase types of fluidization have become familiar. The dense phase is encountered in the reactor and stand pipes, while the dilute phase exists in piping which leads to the reactor and through which the flowing hydrocarbon vapors convey the catalyst into the reactor[14]. Patterson[31] divided fluidized beds into three types: high density, used in stand pipes; medium density, used in reactors; and low density, used in lines transferring the fluid mixture.

Fluidization Processes. Lewis et al[20] classified fluidization processes into continuous and batch types. In the continuous process, the solid particles move continuously through the fluidization unit. In the batch process, no attempt is made to return entrained particles to the bed.

Elutriation. Leva[10] has defined elutriation as the process of separating a mixture of finely divided solids into individual components with the aid of a fluid current.

Attrition. Attrition[10] is the break-down of particles by rubbing and collision in a turbulently fluidized bed of solids. Leva[10] has discussed qualitatively a limiting mass velocity above which attrition rates are high and prohibit prolonged operation. This limiting velocity, of course, depends upon the physical properties of the solid.

Principles of Fluidization

The fluidized state is achieved[33] when a bed of particles is brought into a continuously agitated state by an upwardly moving stream of fluid. When a stream of gas or liquid is passed through a mass of solid particles, reproducible changes in physical behavior[29] are observed which pass successive stages as the fluid velocity is increased.

Fluidization Stages. When the velocity of a gas or liquid flowing up through a mass of solid particles is insufficient to lift or support any of the solid, the mass is called a fixed bed[29], or a moving bed, depending on whether the solid is stationary or moving with respect to the containing vessel. With further slight increases in the fluid velocity, the particles are fully supported and the expanding bed becomes fluidized[29]. Just at the point of fluidization, or the critical mass velocity, the mass may form a quiescent fluidized bed[29]. Finally, if the fluid velocity is still further increased, or if the solids feed rate is too low, the surface of the fluidized bed disappears and the whole mass becomes a dispersed suspension.

Behavior of a Bed of Solid Particles at the Critical Mass Velocity. At the critical mass velocity, the particles are fully supported by the fluid[29]. Murphy[29] stated that just at the point of fluidization the mass may form a quiescent fluidized bed. Experimental data have indicated that before fluidization could begin, a definite amount of expansion was necessary, which depended entirely on the original bed density for any one material. The limiting bed density at which fluidization begins has been termed "maximum fluid density", and the fractional voids associated with this condition have been called "minimum fluid voidage"[11].

Important Characteristics of a Fluidized Bed and Solids. The following discussion contains a description of various characteristics of a fluidized bed and solids. The discussion includes voidage, particle density, and particle diameter.

Voidage. Observations[19] have indicated that a bed of fine, solid particles must have a certain minimum voidage before the particles in the bed are sufficiently disengaged from each other to permit free motion within the bed. Leva et al[18] noted from a suty of fluidization characteristics of an irregularly-shaped, iron, Fischer-Tropsch catalyst

that minimum fluid voidage depended upon the shape of the particles as well as upon the effective particle diameter. Leva et al[11] further stated that the minimum fluid voidage was greater for sharp, rough particles than for round, smooth particles. Beds of small particles have larger minimum voidage than do large particles and the actual height of the bed of fixed particles before fluidization does not have any effect on the minimum fluid voidage[12].

Particle Density. Lewis et al[20] have shown that the critical mass velocity was directly proportional to the density of the solids. Matheson et al[23] noted that increasing the density of the solids increased the maximum bed density. Morse[28] found that segregation was favored by increased particle density. Ketternring et al[9] observed that for a given size of particle, mass and heat transfer coefficients increased with increasing particle density because of an increase in slip velocity with particle density.

Particle Diameter. Leva et al[12] reported that the minimum fluid voidage increased with a decrease in particle diameter, and that slugging was favored by large particles. Similarly, Miller and Logwinuk[26] have shown that the critical mass velocity, for particles of a given density, increased with increasing particle size. Lewis et al[21] observed that for a given length-to-diameter ratio of a bed, the pressure drop across fluidized beds increased with an increase in particle size. Leva et al[15] observed that channeling was favored by fine particles, whereas Morse found that segregation of particles[27] increased with increasing particle size. Also, Leva et al[13] reported that the smooth range of fluidization was larger for small particles than for large ones.

Mathematical Correlations

Great differences exist in the methods employed by various investigators in making experimental measurements[8] for particle size, density measurements, fraction voids, and the like. Each time a new investigation on fluidization is planned, it is necessary to specify the procedures to be followed in detail. Campbell[4] explained that many of the mathematical relationships developed in fluidization are satisfactory for some commercial uses, yet they are unsafe in universal application. The mathematical correlations to be discussed are determination of particle diameter, particle density, and fraction voids.

Determination of Particle Diameter. The two best methods for determining the particle diameter of spherical particles is relatively an easy matter as long as the solids are uniform in size. Magnified photographs or the microscope are easily utilized.

Gregg(7) has presented a method for determining particle size based on the average projected length and breadth of at least 20 representative particles. Gregg's correlation may be stated as follows:

$$D_p = \sqrt{\frac{4 \times C \times B \times L}{\pi}} \qquad (1)$$

where:

D_p = average particle size in.

B = average breadth or width of the particles perpendicular to the longest axis of the particles, in.

L = average length of the particles along the longest axis of the particles, in.

C = an experimentally determined constant equal to 0.77 for rounded particles and 0.75 for rough particles, dimensionless.

Gregg has pointed out that the average breadth, B, is related to the size of the aperture in a sieve through which the particles will pass.

The most common method for determining the average particle size is the weighted geometric mean method[25], which is as follows:

$$D_p = \prod_{y=1}^{y=y} X \times d_{pgm} \qquad (2)$$

where:

D_p = geometric mean particle diameter, in.

y = number of sieved components in the solids mixture

$d_{pgm} = \sqrt{d_1 \times d_2}$ = geometric mean diameter of component retained between adjacent sieves having aperature sizes d_1 and d_2, in.

X = weight fraction of closely screened material.

It was reported by Leva et al[17] that the geometric mean particle size correlated well in fluidization studies.

Particle Density. The density or specific gravity of solids is generally obtained by means of water displacement using pycnometers or various specific gravity bottles which are available for this purpose[16]. The equation used with the above method is as follows:

$$\rho_p = \frac{W_1 \times s_1 \times d_1}{W_2 - W_3 \left(\frac{s_1}{s_2}\right)} \qquad (3)$$

where:

ρ_p = absolute density of solid particles, lb/ cu ft

W_1 = dry weight of solids, gm

s_2 and s_1 = specific gravity of water at temperature T_1 and T_2

d_1 = density of water at temperature T_1, lb/cu ft

W_2 = weight of water to fill gravity bottle at T_1, gm

W_3 = weight of water to fill gravity bottle at temperature T_2 minus weight of water displaced by solid particles at temperature T_2, gm.

Voidage. The fraction voidage volume within a bed of solids may be obtained from the following equation[34]:

$$\gamma = (L-L_o)/L \qquad (4)$$

where:

γ = fraction voids, demensionless

L = height of bed containing voids, ft

L_o = height of voidless bed, ft

$L_o = W/\rho_p A$

where:

W = weight of solids charged into vessel, lb

ρ_p = absolute density of solids, lb/cu ft

A = cross-sectional area of vessel, sq ft.

III. EXPERIMENTAL

The experimental portion of this investigation includes the purpose of investigation, plan of experimentation, materials and apparatus, method of procedure, data and results, and sample calculations.

Purpose of Investigation

The purpose of the investigation was to determine the mean particle diameter, density, and the fraction voids of Ottawa sand (20-to 30-mesh, 30-to 50-mesh, 50-to 70-mesh) to be used in extended studies on fluidization.

Plan of Experimentation

The plan of experimentation followed in this investigation consisted of a review of literature on fluidization, selection of materials, and performance of tests.

Literature Review. The literature review included a study of the history of fluidization and the reasons for the rapid acceptance of fluidization as a new unit operation in chemical engineering. Applications of fluidization to various chemical processes were noted and the advantages and disadvantages of fluidized beds were discussed. The terminology employed in fluidization was reviewed and a study was made of past work performed by several investigators. The effects of the physical properties of the fluidizating medium were discussed in relationship to particular properties (mean particle diameter, density, and fraction voids).

Selection of Materials. The solid particles used in this investigation were desired to have a range in particle size from 20-mesh to 70-mesh, spherical in shape, and constant density: The material chosen was Ottawa sand (20-to 30-mesh, 30-to 50-mesh, 50-to 70-mesh).

Performance of Tests. The procedure followed in the performance of tests consisted of several steps. The particle diameter was determined by two methods, enlargement of

photographs and geometric mean. The particle density was determined by using a Hogarth specific gravity bottle. The fraction voids were determined by finding the percentage void volume.

Materials

The specifications for the materials used in this investigation are presented as follows:

Air: Compressed air, humidity 0.006 pound of water per pound of dry air. Supplied by nash hytor compressor, Department of Chemical Engineering, Virginia Polytechnic Institute, Blacksburg, Va. Used as fluidization medium and as heat transfer medium for regenerating indicating drierite.

Carbon Tetrachloride. Lot No G)54J; C.P.; Code No 1556; boiling range, 75-77° C; 0.02 weight per cent nonvolatile; 0.006 weight per cent sulfur; molecular weight, 153.84. Made and distributed by General Chemical Division, Allied Chemical and Dye Corp., New York, N. Y. Used as manometer fluid for indicating the pressure drop across fluidized beds of solid particles.

Drierite. Indicating; 6-mesh (U.S. Standard); bulk density, 54 to 60 pounds per cubic foot; anhydrous calcium sulfate coated with C.P. cobalt chloride; regenerated at 375° F in two hours. Obtained from W. A. Hammond Drierite Company, Xenia, Ohio. Used as drying agent for removing moisture from fluidizing medium (air).

Mercury. Obtained from Fisher Scientific Co., Silver Spring, Md. Used as manometer fluid of orifice meter in air line to fluidization column.

Sand. Ottawa sand; absolute density, 166.6 pounds per cubic foot; 20-to 30-mesh, 30-to 50-mesh, 50-to 70-mesh (Tyler Standard); weighted, geometric mean particle diameter, 0.02530 inch, 0.01691 inch, 0.00981 inch, respectively; meets specifications of A. S. T. M. Designation C-190. Obtained from Ottawa Silica Co., Ottawa, Ill. Used as the solid components for the fluidized beds studied.

Water, Distilled. Obtained from laboratory still in the Department of Chemical Engineering, Virginia Polytechnic Institute, Blacksburg, Virginia. Used in absolute density determinations for solid particles.

Apparatus

The apparatus used in this investigation are described as follows:

Analytical Balance. Chain-o-matic, 250-gram capacity graduated in one-gram increments. Obtained from Seederer-Kolbusch, Inc., Jersey City, N. J. Used for weighing solid particles for density determinations.

Beam Balance. Stainless steel, 610-gram capacity, graduated in 1/10,000 of a gram. Made by Ohaus and Co., Newark, N. J. Distributed by Schaar and Co., Chicago, Ill. Used for weighing solid particles used in sieve analysis.

Gyratory Riddle. Combs, model s-102. Obtained from Great Western Manufacturing Co., Leavenworth, Kans. Used for shaking sieves in screen analysis of solid particles.

Hot Plate. Autemp heater, 115 v, ac, 450 w. Obtained from Fisher Scientific Co., Silver Spring, Md. Used in density determinations for solid particles to boil suspensions to expel entrapped air from particles.

Miscellaneous Glassware. Several pieces of laboratory glassware such as beakers, flasks, test tubes, and glass funnels were obtained from Fisher Scientific Co., Silver Spring, Md. Used for miscellaneous purposes.

Oven. Electric; inside size 12 x 18 inches, 12 inches high; 110 v, 660 w, range, 0-500°F. Obtained from Will Corp., Rochester, N. Y. Used to dry particles for density determinations.

Sieves. No 16, 20, 30, 40, 50, 70, 100 (Tyler Standard); complete with lid and pan; brass; 8-inch diameter. Obtained from the W. S. Tyler Co., Cleveland, Ohio. Used for screen analysis of solid particles.

Specific Gravity Bottle. Hogarth, A. S. T. M.; 100-ml, pyrex glass. Obtained from Fisher Scientific Co., Silver Spring, Md. Used for determining absolute density of solid particles.

Thermometers. Mercury in glass, range, 0-300° F, graduated in 2° F increments; 3-inch immersion. Obtained from Fisher Scientific Co., Silver Spring, Md. Used to measure temperatures of the solid particles in the absolute density determination.

Timer. Electric, "Precision Time It", 0-9999.0 seconds, graduated in 1/10 of a second, 115 v, 60 cy, 5 w. Obtained from Precision Scientific Co., Chicago, Ill. Used in determining the time for shaking in the sieve analysis.

Weighing Bottles. Ground-glass stoppered, 60 ml, catalog No 3-415. Obtained from Fisher Scientific Co., Silver Spring, Md. Used in the absolute density determinations.

Weights. Analytical balance weights, Code No 61-A, 100 gm combined weight, stainless steel. Made and distributed by Voland and Sons, Inc., New Rochelle, N. Y. Used with analytical balance.

Method of Procedure

The method of procedure followed in the performance of this investigation for determing the characteristics of the solid particle included absolute density determinations, screen analyses for determining the weighted, geometric mean diameters, enlargement of photographs to determine the mean diameters, and fraction voids.

Density Determinations. The absolute densitites of the solid particles studied were determined with a 100-milliliter, Hogarth specific gravity bottle as follows: A 60-milliliter, stoppered weighing bottle was filled about three-fourths full with a sample of the solid particles to be tested, and placed in an electric over at 400 degrees Fahrenheit for twenty-four hours to dry the material. After removing the sample from the oven, the material was desiccated until cool. A clean, Hogarth specific bottle was tared and filled with distilled water, being careful to expel all air from the bottle. The outside of the bottle was wiped dry, the bottle and water rapidly weighed, and the temperature,(T_1), measured with a thermometer immediately

after the weight of the bottle and water were recorded. Half of the water was poured out of the bottle, and a previously-weighed quantity of the dried particles was placed in the gravity bottle such that the bottom was covered to not more than 1/4 inch. The gravity bottle was then placed on a hot plate and the suspension boiled for one hour to expel all air from the material. After cooling the contents of the gravity bottle to ambient temperature, the bottle was filled with distilled water, the outside of the bottle was wiped dry, and the weight of the bottle and contents were rapidly taken. After the weight was recorded, the temperature, (T_2), of the contents of the bottle was immediately determined. The density of the solid particles was then calculated by means of equation 3, page 18.

Screen Analyses. Screen analyses were performed on representative samples of each range of the solid particles studied in order to determine the average particle size of the materials. Samples of 100 grams were used with sieves eight inches in diameter. The sieves were arranged so that the sizes of the aperatures of adjacent sieves were related by the multiplier, square root of two. The weighted, geometric mean, particle diameter was calculated for each sand size by means of equation 2, page 17.

Size Analysis by Photograph Means. Magnified photographs were used to determine the particles sizes of the sand. To determine the particle size by magnified photographs 20 representative particles of each size were studied as shown in Figure 1, page 31. The photographs were made such that length measurements could be read directly. The magnification used in making the photographs was 29.5. The particle diameter using the magnified photographs was calculated for each of the sand sizes by means of equation 1, page 16.

Fraction Voids. The fraction voids for the 20- to 30-, 30-to 50-, and 50-to 70-mesh ranges of the Ottawa sand were determined by using 2- and 4-inch diameter copper tubes six inches in height. After taring the 2-inch copper tube, it was filled with the 20-to 30-mesh Ottawa sand and weighed. Knowing the absolute density of the sand, the fraction voids were calculated by using equation 4, page 19. Duplicate tests were carried out for each sand size using both the 2- and 4-inch copper tubes.

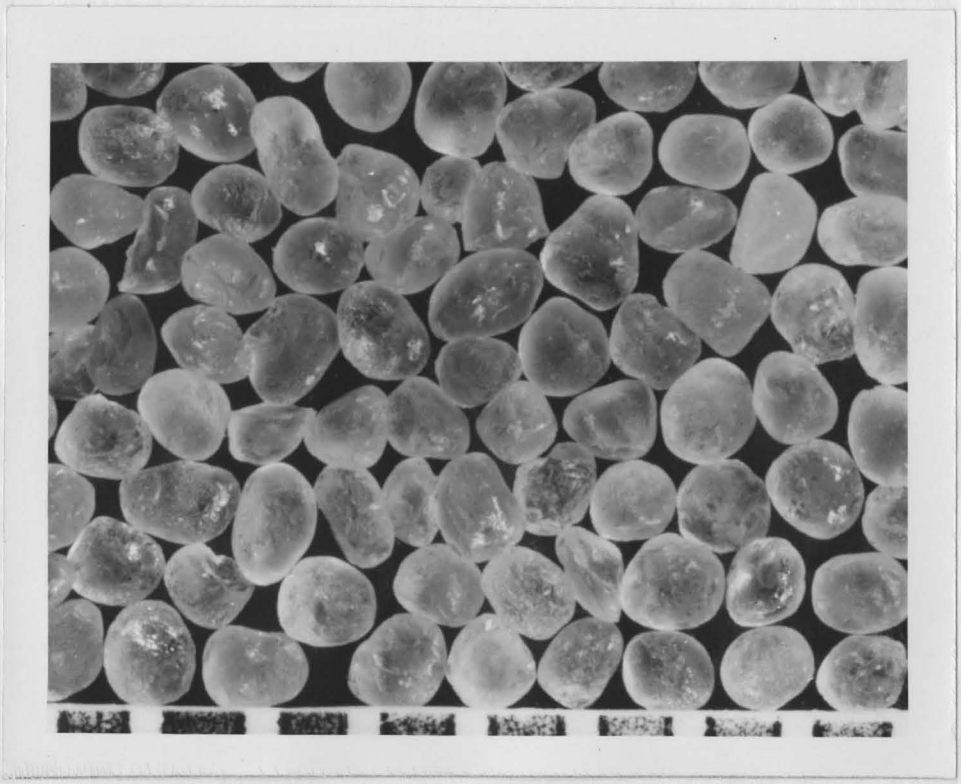

FIGURE 1. ENLARGEMENT OF 20-TO 30-MESH OTTAWA SAND FOR PARTICLE DIAMETER DETERMINATION

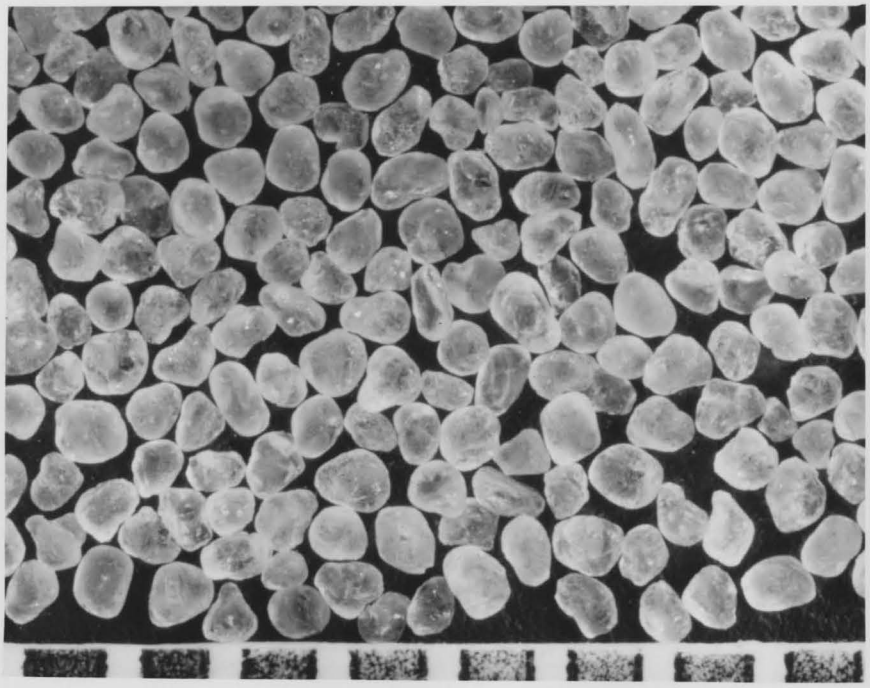

FIGURE 2. ENLARGEMENT OF 30-TO 50-MESH OTTAWA SAND FOR PARTICLE DIAMETER DETERMINATION

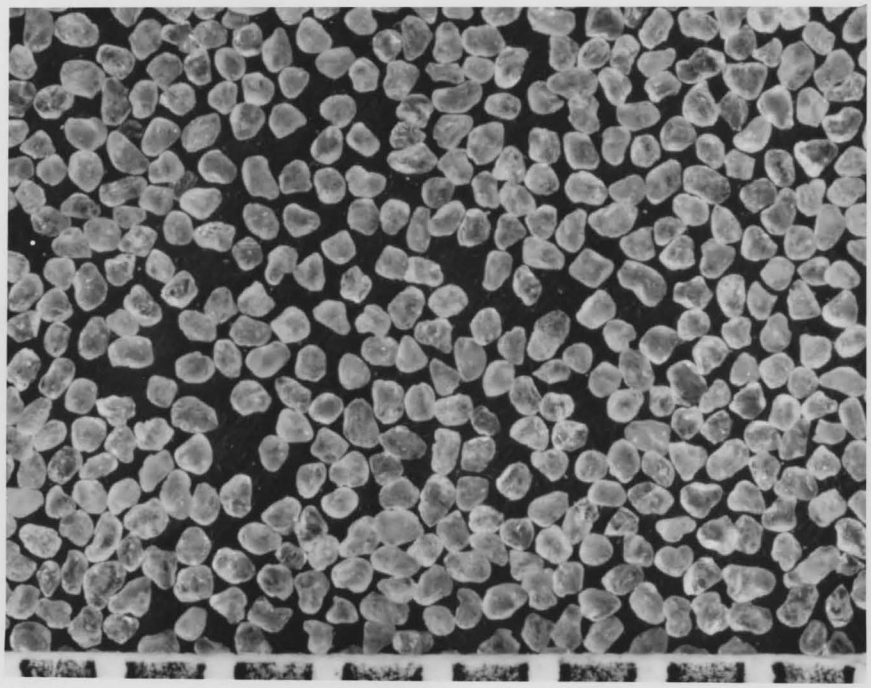

FIGURE 3. ENLARGEMENT OF 50-TO 70-MESH OTTAWA SAND FOR PARTICLE DIAMETER DETERMINATION

Data and Results

The data and results of this investigation are presented on the following pages.

Particle Density. The particle densities of the ranges, 20-to 30, 30-to 50, and 50-to 70-mesh, of Ottawa sand are presented in Table I, page 35.

Screen Analyses. The results of screen analyses of the ranges, 20-to 30, 30-to 50, and 50-to 70-mesh of Ottawa sand for determining the weighted, geometric mean, particle diameters of the particles are presented in Table II, page 36.

Magnified Photographs. The measurements taken on the magnified photographs for determining the mean particle diameters of the three sizes of Ottawa sand are presented in Table III, page 37.

Fraction Voids. The data determining the fraction voids of the three ranges, 20-to 30, 30-to 50, and 50-to 70-mesh, of Ottawa sand are shown in Table IV, page 38.

TABLE I

Density of Ottawa Sand

Test No	Sand Size Mesh[a]	Weight of Bottle[b] gm	Weight of Bottle and Distilled Water gm	Weight of Sand Sample gm	Weight of Bottle and Contents gm	Temperature of Distilled Water °F	Temperature of Contents °F	True Density gm/cc	True Density lb/ft^3
1	20 to 30	41.4546	157.5913	10.0077	163.8557	75	72	2.67	166.1
2		41.4546	157.5913	10.0002	163.8187	75	74	2.72	169.1
3		41.4546	157.5913	10.0009	163.8101	75	74	2.64	164.2
4	30 to 50	41.4546	157.5913	10.0018	163.8426	72	71	2.67	166.0
5		41.4546	157.5913	10.0044	163.8152	71	73	2.65	165.0
6		41.4546	157.5913	10.0023	163.8944	70	68	2.70	168.0
7	50 to 70	41.4546	157.5913	10.0023	163.8651	71	69	2.68	166.8
8		41.4546	157.5913	10.0010	163.8744	70	70	2.69	167.5
								Average	166.6

[a]Tyler screen scale.

[b]Hogarth specific gravity bottle.

TABLE II

Screen Analyses of Ottawa Sand for Determining of Particle Size

Test No	Sand Size Mesh	Tyler Sieve Series, Sieve No	Sieve Aperture, in.	Material Retained, wt%	$\sqrt{d_1 d_2}$ [a], in.	d_p [b], in.	D_p [c], in.	Average D_p, in.
1	20 to 30	16	0.0464	0.00	-------	-------	0.02537	
		20	0.0328	1.54	0.03800	0.00051		
		30	0.0232	71.40	0.02760	0.02191		
		40	0.0164	8.80	0.01950	0.00193		
		50	0.0116	4.68	0.01380	0.00064		
		70	0.0082	2.05	0.00975	0.00020		
		100	0.0058	1.59	0.00689	0.00018		
2		16	0.0464	0.00	-------	-------	0.02532	
		20	0.0328	1.95	0.03800	0.00074		
		30	0.0232	77.91	0.02760	0.02123		
		40	0.0164	12.82	0.01950	0.00211		
		50	0.0116	5.91	0.01380	0.00082		
		70	0.0082	3.44	0.00975	0.00034		
		100	0.0058	1.97	0.00689	0.00007		
3		16	0.0464	0.00	-------	-------	0.02521	
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	77.80	0.02760	0.02203		
		40	0.0164	11.10	0.01950	0.00197		
		50	0.0116	5.06	0.01380	0.00084		
		70	0.0082	3.03	0.00975	0.00030		
		100	0.0058	1.01	0.00689	0.00007		
4	30 to 50	16	0.0464	0.00	-------	-------	0.01677	0.02530
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	5.53	0.02760	0.00015		
		40	0.0164	55.00	0.01950	0.01036		
		50	0.0116	34.77	0.01380	0.00590		
		70	0.0082	4.70	0.00975	0.00036		
		100	0.0058	0.00	0.00689	-------		
5		16	0.0464	0.00	-------	-------	0.01690	
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	0.52	0.02760	0.00014		
		40	0.0164	55.20	0.01950	0.01076		
		50	0.0116	41.70	0.01380	0.00575		
		70	0.0082	2.58	0.00975	0.00025		
		100	0.0058	0.00	0.00689	-------		
6		16	0.0464	0.00	-------	-------	0.01703	
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	2.00	0.02760	0.00055		
		40	0.0164	54.30	0.01950	0.01059		
		50	0.0116	40.70	0.01380	0.00562		
		70	0.0082	3.00	0.00975	0.00029		
		100	0.0058	0.00	0.00689	-------		0.01691
7	50 to 70	16	0.0464	0.00	-------	-------	0.00976	
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	0.00	0.02760	-------		
		40	0.0164	0.00	0.01950	-------		
		50	0.0116	3.04	0.01380	0.00028		
		70	0.0082	95.40	0.00975	0.00930		
		100	0.0058	2.56	0.00689	0.00018		
8		16	0.0464	0.00	-------	-------	0.00982	
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	0.00	0.02760	-------		
		40	0.0164	0.00	0.01950	-------		
		50	0.0116	3.62	0.01380	0.00050		
		70	0.0082	93.78	0.00975	0.00914		
		100	0.0058	2.60	0.00689	0.00018		
9		16	0.0464	0.00	-------	-------	0.00984	
		20	0.0328	0.00	0.03800	-------		
		30	0.0232	0.00	0.02760	-------		
		40	0.0164	0.00	0.01950	-------		
		50	0.0116	4.61	0.01380	0.00064		
		70	0.0082	91.82	0.00975	0.00895		
		100	0.0058	3.57	0.00689	0.00025		0.00981

[a] The value $\sqrt{d_1 d_2}$ is the geometric mean of adjacent sieve apertures.

[b] The value d_p is the product of $\sqrt{d_1 d_2}$ and the percentage of material retained between adjacent sieves.

[c] The value D_p is the weighted, geometric mean, particle diameter, equal to Σd_p.

TABLE III

Particle Size of Ottawa Sand[a]

by Magnified Photographs

Sample No	Particle Size 20-to 30-mesh: Length of Particle, in.	Width of Particle, in.	Particle Diameter, in.	Particle Size 30-to 50-mesh: Length of Particle, in.	Width of Particle, in.	Particle Diameter, in.	Particle Size 50-to 70-mesh: Length of Particle, in.	Width of Particle, in.	Particle Diameter, in.
1	0.0354	0.0307	0.0324	0.0194	0.0187	0.0187	0.0114	0.0094	0.0101
2	0.0307	0.0257	0.0276	0.0247	0.0187	0.0211	0.0107	0.0100	0.0102
3	0.0254	0.0234	0.0239	0.0200	0.0180	0.0186	0.0120	0.0107	0.0111
4	0.0314	0.0287	0.0294	0.0200	0.0167	0.0182	0.0120	0.0107	0.0111
5	0.0307	0.0254	0.0274	0.0214	0.0174	0.0189	0.0120	0.0100	0.0108
6	0.0275	0.0240	0.0257	0.0167	0.0154	0.0158	0.0107	0.0107	0.0105
7	0.0287	0.0266	0.0272	0.0194	0.0180	0.0184	0.0107	0.0107	0.0105
8	0.0254	0.0254	0.0250	0.0214	0.0200	0.0203	0.0134	0.0127	0.0128
9	0.0334	0.0300	0.0316	0.0227	0.0221	0.0220	0.0107	0.0127	0.0114
10	0.0307	0.0257	0.0276	0.0200	0.0187	0.0190	0.0120	0.0107	0.0111
11	0.0280	0.0260	0.0265	0.0187	0.0147	0.0163	0.0120	0.0087	0.0100
12	0.0280	0.0257	0.0267	0.0187	0.0174	0.0177	0.0094	0.0100	0.0095
13	0.0280	0.0247	0.0258	0.0187	0.0180	0.0180	0.0120	0.0094	0.0104
14	0.0307	0.0208	0.0293	0.0214	0.0200	0.0203	0.0120	0.0120	0.0118
15	0.0294	0.0260	0.0271	0.0221	0.0214	0.0214	0.0120	0.0107	0.0111
16	0.0314	0.0267	0.0284	0.0234	0.0200	0.0216	0.0120	0.0094	0.0104
17	0.0347	0.0280	0.0312	0.0221	0.0180	0.0196	0.0120	0.0100	0.0108
18	0.0300	0.0300	0.0295	0.0187	0.0180	0.0180	0.0120	0.0100	0.0108
19	0.0307	0.0247	0.0270	0.0200	0.0180	0.0186	0.0120	0.0107	0.0111
20	0.0294	0.0247	0.0264	0.0221	0.0200	0.0206	0.0120	0.0094	0.0104
Average			0.0278			0.0191			0.0108

[a]The three sizes of Ottawa sand are 20-to 30-mesh, 30-to 50-mesh, and 50-to 70-mesh.

TABLE IV

Fraction Voids of Ottawa Sand

Sand Size Mesh	Column Diameter, in.	Height of Vessel, ft	Weight of Solids, lb	Cross-sectional Area of Vessel, sq ft	Fraction Void,[a] per cent
20 to 30	2	0.5	1.14	0.0218	37.1
	4	0.5	4.49	0.0872	38.2
30 to 50	2	0.5	1.12	0.0218	38.7
	4	0.5	4.31	0.0872	40.7
50 to 70	2	0.5	1.07	0.0218	41.3
	4	0.5	4.16	0.0872	42.7

[a]Average of three test using 2-and 4-inch diameter columns.

Sample Calculations

A sample of each calculation made in computing the results of this investigation are presented on the following pages.

Particle Density. The absolute density of the solid particles studied in this investigation was determined by water displacement with a Hogarth, specific gravity bottle. The calculation of the particle density for the Ottawa sand, Table I, page 35, is illustrated below, using equation 3, page 18.

$$\rho_p = \frac{W_1 \times s_1 \times d_1}{W_2 - W_3 (s_1/s_2)}$$

$$\rho_p = \frac{(gm) \times (lb/cu\ ft \times cu\ ft/gm) \times (lb/cu\ ft)}{(gm) - (gm) \times (lb/cu\ ft \times cu\ ft/lb)}$$

where:

ρ_p = absolute density of solid particles, lb/cu ft

W_1 = dry weight of solids, gm

W_2 = weight of water to fill gravity bottle at T_1, gm

W_3 = Weight of water to fill gravity bottle at temperature T_2 minus weight of water displaced by solid particles at T_2, gm

T_1 = 75 °F (0.99736)

T_2 = 72 °F (0.99774)

$$\rho_p = \frac{10.0077 \times 0.99736 \times 62.4}{(116.1367 - 112.3934 \times 0.99774/0.99736)}$$

ρ_p = 166.1 lb/cu ft.

Particle Diameter. The weighted, geometric mean, particle diameter was evaluated from screen analyses of the various solid particles in this investigation. The calculation of the particle diameter for the 50-to 70-mesh Ottawa sand, Table II, page 36, is illustrated below, using equation 2, page 17.

$$D_p = \begin{cases} y = y \\ X\ d_{pgm} \\ y = 1 \end{cases}$$

$$D_p = \begin{cases} y = y \\ \quad (lb/lb)\ (in.) \\ y = 1 \end{cases}$$

where:

D_p = weighted, geometric mean particle diameter, in.

y = number of sieved components in the solids mixture

$d_{pgm} = \sqrt{d_1 \times d_2}$ = geometric mean diameter of component retained adjacent sieves having aperatrue sizes $\underline{d}_1$ and $\underline{d}_2$, in.

X = weight fraction of closely screened material retained between adjacent sieves of a square root-of-two series of screens

$$D_p = 2.04 \times (0.0164 \times 0.0116)^{\frac{1}{2}} + 95.40 \times (0.0116 \times 0.0082)^{\frac{1}{2}} + 2.56 \times (0.0082 \times 0.0058)^{\frac{1}{2}}$$

$$D_p = 0.00976 \text{ in.}$$

Particle Diameter by Magnified Photographs. The average particle size was evaluated by magnified photographs. The enlargement of the particles was 29.5 using 20 representative particles. The calculation of the particle diameter for the 50-to 70-mesh Ottawa sand, Table III, page 37, is illustrated below, using equation 1, page 16.

$$D_p = \sqrt{\frac{4 \times C \times B \times L}{\pi}}$$

where:

D_p = average particle size, in.

B = average breadth or width of the particles perpendicular to the longest axis of the particles, in.

L = average length of the particles along the longest axis of the particles, in.

C = 0.76

$$D_p = \sqrt{\frac{4 \times 0.76 \times 0.100 \times 0.0120}{\pi}}$$

$$D_p = 0.0108 \text{ in.}$$

Fraction Voids. The fraction voids in a fluidized bed of solid particles for any particular rate of fluid passing through the bed was calculated as is illustrated below for 50-to 70-mesh Ottawa sand in a two-inch vessel, test 1, Table IV , page 38.

$$E = \frac{L - (W/\rho_p A)}{L} \times 100$$

$$E = \frac{(ft) - (lb/lb\text{-}cu\ ft\text{-}sq\ ft)}{(ft)}$$

where:

E = fraction void, volume per cent

L = bed depth, ft

W = weight of solid particles in bed, lb

ρ_p = absolute particle density, lb/cu ft

A = cross-sectional area of vessel, sq ft

$(W/\rho_p A)$ = L_o = voidless bed depth, ft

$$E = \frac{0.5 - (1.14/166.6 \times 0.0218)}{0.5} \times 100$$

$$E = 37.1\ \%.$$

IV. DISCUSSION

The results obtained during this investigation are discussed, recommendations for future work are presented, and the limitations imposed upon the investigation are stated in this section.

Discussion of Results

The discussion of results deals with the particle diameter by screen analyses, particle diameter by magnified photographs, determination of absolute density of solid particles, fraction voids, and experimental errors.

Particle Diameter by Screen Analyses. Weighted, geometric mean, particle diameters were calculated for the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand in this investigation from screen analyses, which are presented in Table II, page 36. For each of the ranges of the Ottawa sand three tests were made and the discrepancy between these tests for each range was less than 0.5 per cent. The weighted, geometric mean, particle diameters of the 20-to 30,

30-to 50, and 50-to 70-mesh Ottawa sand were 0.02530, 0.01691, and 0.00981 inch, respectively. For the 20-to 30-mesh Ottawa sand 79.40 per cent was retained on the 30-mesh sieve(Tyler Sieve Series), for the 30-to 50-mesh Ottawa sand 42.77 per cent was retained on the 50-mesh sieve (Tyler Sieve Series), and for the 50-to 70-mesh Ottawa sand 95.40 per cent was retained on the 70-mesh sieve (Tyler Sieve Series). For each size the amount to be retained on the 30-, 50-, and 70-mesh sieve was 95 per cent as sold.

Particle Diameter by Magnified Photographs. The average particle diameters were determined for the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand in this investigation by magnified photographs, which are presented in Table III, page 37. Twenty representative samples of each of the three ranges were utilized in determining the average particle diameter. The average particle diameter of the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand were 0.0278, 0.0191, and 0.0108 inch, respectively. The discrepancy between the particle diameters of the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand were 11.2, 12.9, and 10.1 per cent, respectively.

The difference between the particle diameter as determined by the magnified photographs and screen analyses was the shape factor of 0.76. In the magnified photographs, two diameters were measured perpendicular to each other and using equation 1, page 16, the average diameter was determined. But in using this equation a shape factor had to be introduced, and Gregg[7] determined this shape factor equal to 0.77 for rounded particles and 0.75 for rough particles. For the Ottawa sand an average of the two was chosen as 0.76. Therefore, the difference between the screen analyses and the magnified photographs was in the value assumed for the shape factor.

Determination of Absolute Density of Solid Particles. The absolute densities of solid particles are generally determined by water displacement and in this investigation the absolute density was determined by water displacement using a Hogarth specific gravity bottle. But the amount of water displaced by the particles was measured, the Ottawa sand was placed in a gravity bottle, half filled with water, and boiled for one hour on a hot plate to expel the air from the voids. Occasionally, the bottle was removed from the hot plate and shaken to agitate the

particles. After twenty minutes, the air was believed to have been removed from the voids by boiling and agitation, because bubbles were observed to have ceased being released from the particles. However, the sand particles were boiled for an hour to insure complete air removal from the sand. As a check, several density determinations were made on each of the three ranges of Ottawa sand (20-to 30, 30-to 50, and 50-to 70-mesh). The results obtained varied less than 0.5 per cent for any given sand range. The average absolute density for the three ranges of Ottawa sand (20-to 30, 30-to 50, and 50-to 70-mesh) was 166.6 pounds per cubic foot as shown in Table I, page 35.

Fraction Voids. The fraction voids as shown in Table IV, page 38, were calculated for the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand in this investigation by using 2- and 4-inch diameter tubes which are six inches in height. Knowing the weight of the sand (20-to 30, 30-to 50, and 50-to 70-mesh) required to fill one of these tubes and the absolute density, by using equation 4, page 19, the fraction voids for the three ranges could be calculated.

The fraction voids for the 20-to 30-mesh Ottawa sand in the 2-and 4-inch tubes were 37.1 and 38.2 per cent. For the 30-to 50-mesh Ottawa sand in the 2-and 4-inch tubes, the fraction voids were 38.7 and 40.7 per cent. The 50-to 70-mesh Ottawa sand in the 2-and 4-inch tubes had fraction voids of 41.3 and 42.7 per cent, respectively. As the sand particles decrease in size the fraction voids show a slight increase.

Experimental Errors. Possible sources of errors in this investigation were to be found in magnified photographs and fraction voids.

Errors in Magnified Photographs. The magnified photographs were made with a scale and after the enlargement it caused difficulty in reading the correct magnification. Twenty sand particles were used to determine the particle diameter and varied for the 20-to 30-mesh Ottawa sand from 0.0324 to 0.0239 inches in diameter but gave an average for the twenty particles of 0.0278 inch in diameter. The twenty sand particles taken for the average were chosen at random, trying to get some small, medium, and large ones combined.

Errors in Determining Fraction Voids. The fraction voids were determined by using 2-and 4-inch diameter tubes which were six inches in height, and the assumption was made that for a tube twelve inches high or more and either 2- or 4-inches in diameter, the fraction voids would be proportional to the height.

Recommendations

The following recommendations were made after completing this investigation.

Fraction Voids Determined for Each Bed Height. The fraction voids as determined gives results only for one bed height. The fraction voids should be determined for each bed height so that a true relationship to bed height for fraction voids would result. Therefore, tubes 2- and 4-inches in diameter and 3.5 feet in height should be used instead of tubes 2- and 4-inches in diameter and six inches in height.

Enlargement Scale. The smallest reading that could be read on the scale used was 0.0625 inches before enlargement. After magnification the 0.0625 inch was enlarged 29.5 times making the 0.0625 inch equal to 1.84 inch. A scale that reads hundredth's of an inch would only increase the 0.01 inch reading to 0.295 inches thus giving increased accuracy.

Limitations

The limitations imposed upon this investigation are presented in the following paragraphs.

Temperature. The ambient temperature during the density determination was 76 degrees Fahrenheit. The temperature of the distilled water used in the density determinations was 75 degrees Fahrenheit. The sand samples for the density determinations were dried at a temperature of 400 degrees Fahrenheit.

Time. In the density determination the sand samples were dried for 24 hours and boiled with distilled water for one hour. In determining the mean particle diameter by screen analyses, the gryatory riddle was operated for seven minutes.

Materials Tested. The materials studied in this investigation consisted of 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand.

Sand Size. The weighted, geometric mean particle diameters of the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand were determined from screen analyses. The

particle sizes for the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand are 0.02530, 0.01691, and 0.00981 inch diameter, respectively.

Magnification. The average particle diameters of the 20-to 30, 30-to 50 and 50-to 70-mesh Ottawa sand were determined by magnified photographs. The magnification at which the average diameters was determined was 29.5. The particle sizes for the 20-to 30, 30-to 50, 50-to 70-mesh are 0.0278, 0.0191, 0.0108 inches in diameter.

Equipment for Fraction Voids. The fraction voids were determined using 2- and 4-inch diameter tubes which were six inches in height.

V. CONCLUSIONS

The investigation "Determination of the Mean Particle Diameter, Density, and Fraction Voids of Ottawa Sand" performed at an ambient temperature of 76 degrees Fahrenheit, with a magnification for the magnified photographs of 29.5, an absolute density of 166.6 pounds per cubic foot, and the sand particles varied from 0.02530 to 0.00981 inch in diameter. The investigation led to the following conclusions:

1. The average particle diameters as determined by magnified photographs and by screen analyses are not comparible. The particle diameter as determined by both methods for the 20-to 30-mesh Ottawa sand varied 11.2 per cent.

2. The density of the Ottawa sand was 166.6 pounds per cubic foot which agrees within 0.4 per cent of published values.

3. The fraction voids are influenced by the particle size. The fraction voids increased as the particle size of the Ottawa sand decreases. For the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand the fraction voids increased from 37.1 to 41.3 per cent.

VI. SUMMARY

Fluidization is one of the most recent developments in the field of unit operations. It occurs when particles of solids are maintained in a dense turbulent state by means of a moving fluid. The literature pertaining to fluidization covers only limited operating conditions, and the physical variables in fluidization are the characteristics of the retaining vessel, fluidizing medium, and the particles to be fluidized.

The properties of the fluidized solid which are of importance are the size, shape, density, surface tension, and electrostatic charge of the solids, but they have not been fully developed.

The purpose of this investigation was to determine the mean particle diameter, particle density, and the fraction voids of Ottawa sand (20-to 30, 30-to 50, and 50-to 70-mesh) to be used in extended studies on fluidization.

In the above investigation, the mean particle diameters determined by screen analyses for 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand were 0.02530, 0.01691, and 0.00981 inches, respectively. The average particle diameters

determined by magnified photographs for 20-to 30, 30-to 50, 50-to 70-mesh Ottawa sand were 0.0278, 0.0191, and 0.0108 inches, respectively. The absolute density of the Ottawa sand was 166.6 pounds per cubic foot. The fraction voids for the 20-to 30, 30-to 50, and 50-to 70-mesh Ottawa sand in the 2-inch diameter tube were 37.1, 38.7, and 41.3 per cent and in the 4-inch diameter tube 38.2, 40.7, and 42.7 per cent, respectively.

VII. BIBLIOGRAPHY

1. Badger, W. L. and W. L. McCabe; "Elements of Chemical Engineering," p. 661. McGraw-Hill Book Co., Inc., New York, N. Y. 1936. 2 ed.

2. Baxter, G. B. and C. F. Hawkins: Specific Gravity of Porous Solids, J. Am. Chem. Soc., 38, 266 (1916).

3. Brown, G. C.: "Unit Operations," pp. 539-40. John Wiley and Sons, Inc., New York, N. Y., 1950. 1 ed.

4. Campbell, D. L.: Fluidization, A Tool for Chemical Engineers, p. 13. Esso Engineering Department Pamphlet, Standard Oil Co., Elizabeth, N. J., (1948).

5. Drew, T. B. and R. P. Genereaux: Flow of Fluids, "Chemical Engineers' Handbook" (J. H. Perry, Editor), p. 778. McGraw-Hill Book Co., Inc., New York, N. Y., 1941. 2 ed.

6. Fluid Catalytic Cracking, p.6, The Kellog Co., 225 Broadway, New York 7, N. Y., 1945.

7. Gregg, S. J.: "The Surface Chemistry of Solids," pp. 132-38. Reinhold Pub. Corp., New York, N. Y., 1951. 1 ed.

8. Happel, J.: Pressure Drop Due to Vapor Flow Through Moving Beds, Ind. Eng. Chem., 41, 1173 (1949).

9. Kettenring, K. N., E. L. Manderfield, and J. M. Smith: Heat and Mass Transfer in Fluidized Systems, Chem. Eng. Prog., 46, 144 (1950).

10. Leva, M.: Elutriation of Fines From Fluidized Systems, Chem. Eng. Prog., 47, 39 (1951).

11. _____, M. Grummer, M. Weintraub, and M. Pollchick: Fluidization of Solid Non-Vesicular Particles, Chem. Eng. Prog., 44, 619 (1948).

12. ibid, p. 620.

13. ibid, p. 623.

14. _____: Introduction to Fluidization, Chem. Eng. Prog., 44, 511 (1948).

15. ibid, p. 513.

16. ibid, p. 514.

17. ibid, p. 517.

18. _____, and H. H. Storch: A Study of Fluidization of an Iron Fischer-Tropsch Catalyst, Chem. Eng. Prog., 44, 707 (1948).

19. Leva, M. and M. Grummer, M. Weintraub, and H. H. Storch: A Study of Fluidization of an Iron Fischer-Tropsch Catalyst, Chem. Eng. Prog., 44, 709 (1948).

20. Lewis, W. K., E. R. Gilliland, and W. G. Bauer: Characteristics of Fluidized Particles, Ind. Eng. Chem., 41, 1104 (1949).

21. ibid, p. 1107.

22. Matheson, G. L., W. A. Herbst, and P. H. Holt: Characteristics of Fluid Solid Systems, Ind. Eng. Chem., 41, 1099 (1949).

23. ibid, p. 1102.

24. Miller, C. O. and A. K. Logwinuk: Fluidization Studies of Solid Particles, Ind. Eng. Chem., 43, 1220 (1951).

25. ibid, p. 1222.

26. ibid, p. 1223.

27. Morse, R. D.: Fluidization of Granular Solids, Ind. Eng. Chem., 41, 1117 (1949).

28. ibid, p. 1122.

29. Murphy, W. J.: Fluidization Nomenclature and Sumbols, Ind. Eng. Chem., 41, 1249-50 (1949).

30. Patterson, J. A.: Fluidization of Solids, "Chemical 19, Engineering Catalog," p. 85. Reinhold Pub. Corp., New York, N. Y., 1948-49. 33 ed.

31. ibid, p. 86.

32. Physical Chemical Data, "Chemical Engineers' Handbook" (J. H. Perry, Editor), p. 411. McGraw-Hill Book Co., Inc., New York, N. Y., 1941. 2 ed.

33. Wilhelm, R. H. and M. Kwauk: Fluidization of Solid Particles, Chem. Eng. Prog., 44, 201 (1948).

34. ibid, p. 205.

35. ibid, p. 209.

VIII. ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to Dr. F. W. Bull for his guidance and encouragement throughout this investigation.

Appreciation is expressed to Dr. for his aid in making the magnified photographs.

Sincere thanks are expressed to E. C. Moncrief for his daily guidance throughout this investigation.

The vita has been removed from the scanned document