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Centrifugal Filtration Through Beds of Small Spheres.

J. Byron Bingeman

Louisiana State University and Agricultural & Mechanical College

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1957

CENTRIFUGAL FILTRATION THROUGH BEDS OF SMALL SPHERES

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Chemical Engineering

by

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ABSTRACT

It was desired to investigate the flow of incompressible fluids through beds of small spheres of mixed size in centrifugal filters. Accordingly, centrifugal filtration data were taken in the viscous flow region on beds of styrene-divinyl benzene spheres in four mesh sizes: 50/100, 100/200, 200/400, 400/-. The beds were formed in two horizontal laboratory centrifugal filters which were five inches and eleven inches in diameter and capable of a maximum rotational speed of 4000 rpm. In the large basket a maximum force of 2500 Gees could be developed, or a maximum pressure drop of 93 psi at the greatest liquid level used. Cakes were approximately 0.1 to 0.2 inch thick in the small basket and approximately 0.5 inch in the large basket. They were prepared by dropping dry solids into a pool of liquid in the rotating basket. Water was the filtrate in all cases but one in which a glycerol solution was used.

The resistance of the filter medium was obtained by running a blank on the filter medium over the range of speeds to be used in a subsequent filtration run. It was then possible to calculate as a function of the pressure drop through the bed the filtration rate which would occur through the solids only.

Experimental conditions were such that the flow rate was in the viscous region and the cakes were non-compressible. Under such conditions the d'Arcy equation for the flow of incompressible media through unconsolidated beds would be expected to apply with a single value of the permeability.

This was found to be the case. However, experimental values of the resistance coefficient and the permeability were found to differ greatly from those which would be calculated theoretically on the basis of the average measured particle size, excluding fines. This discrepancy and some difficulty in obtaining reproducibility were attributed to fines which were present or possibly to gas blocking of the cake.

The Burak-Storrow and Grace applications of the d'Arcy equation were found to correlate the data. A dimensionless form of the same equation was applied in the correlation of the centrifugal filtration data reported in this work and data taken from the literature.

INTRODUCTION

In 1856 d'Arcy observed that water flowed through a sand bed at a rate proportional to the area of the bed and the difference between the upstream and downstream hydraulic heads, and inversely proportional to the bed thickness. Since that time many investigators have accumulated masses of data in support of numerous valuable theoretical and empirical relationships for correlating and predicting pressure drop, flow rate, and fluid and bed properties. Naturally, certain areas of research have received less attention than others.

Among the areas receiving least attention are: flow through beds composed of particles of identical shape but mixed size, flow through unconsolidated beds composed of small particles, and flow under the influence of a centrifugal driving force. This work investigates the flow of liquids through unconsolidated beds of small spherical particles of mixed sizes in two laboratory centrifugal filters. Experimental conditions are such that the flow is laminar and the cakes are incompressible.

The experimental permeabilities are much smaller than would be predicted by theory, which is attributed to the presence of fines. A dimensionless form of the d'Arcy equation is derived and used to correlate the centrifugal filtration data.

CHAPTER I

Review of Theory

Since the literature on the flow of fluids is voluminous and is covered in many standard references, areas outside the scope of this work will be considered only where necessary for a rounded picture. In general, this review of theory will be pointed to the laminar flow of incompressible fluids through unconsolidated and incompressible beds of small spherical particles of mixed size.

Eisenklam⁹ organizes his description of the flow of fluids through porous media according to the three general methods of correlation: one based on pore dimensions, another on the shape of solid constituents and the third on flow characteristics of the porous mass itself. This organization is followed here.

Flow Theory Based on Pore Dimensions

The theory for laminar flow through pores has been developed from that for laminar flow through a horizontal circular pipe. By equating the shear forces to the pressure gradient of an incompressible fluid in laminar flow, the Poiseuille equation was obtained:

$$u = \frac{g_c d^2 \Delta P}{32 \mu L_p} \text{ --- (1)}$$

u = average velocity

d = diameter of pipe

ΔP = pressure loss

- L_p = length of pipe over which ΔP applies
 μ = absolute viscosity

By taking a bundle of capillaries of uniform size as a model of the porous mass, the Kozeny equation¹⁷ may be derived from equation (1).

$$\frac{\Delta P}{L} = \frac{u\mu}{g_c} \frac{(1-\epsilon)^2}{\epsilon^3} S_o^2 K \quad \text{--- (2)}$$

- where L = depth of bed parallel to average flow
 u = superficial velocity
 ϵ = porosity = vol. of pores/total vol. of mass
 $= 1 - \frac{\rho_c}{\rho_s}$

- ρ_c = bulk density of the cake
 ρ_s = density of particles forming the cake
 S_o = surface area/unit vol. of the particles
 $= 6/d$ for spheres
 d = diameter of spherical particle
 K = Kozeny constant

Experimental evidence indicates a value of $5.0 \pm 10\%$ for the Kozeny constant over a range of porosity of 0.9 to 0.3 for unconsolidated porous masses in which the pores are not oriented.^{6,7} However, variations greater than this have been shown by Coulson⁸ and Wyllie and Gregory.²⁶ Figure 1 indicates the effect which porosity and shape of particle may have on K .

Coulson⁸ finds K to be 4.8 ± 0.2 for spherical particles of uniform diameter in the size range 1/16 in. to 5/16 in. Morcom¹⁹ reports $K = 4.5$ for somewhat larger particles ranging in porosity from 0.35 to 0.45. For mixed sizes of spheres the porosity is affected greatly by the entry

FIGURE 1

Kozeny Constant for Some
Unconsolidated Porous Masses*

1. Cylinders (a) $1/4$ in. diam. $\times$ $1/4$ in.
(b) $1/2$ in. diam. $\times$ $1/4$ in.
2. Cubes $1/4$ in.
3. Triangles $3/16$ in. $\times$ $3/16$ in.
4. Plates (a) $1/4$ in. $\times$ $1/4$ in. $\times$ $1/32$ in. thick
(b) $1/4$ in. $\times$ $1/4$ in. $\times$ $1/16$ in. thick
5. Spheres $1/16$ in. to $5/16$ in. diam.

of small particles into spaces among the larger ones or by bridging. According to Coulson,⁸ K is changed more when the diameter ratio of a mixture of spheres is 5:1 than when it is 2:1. At the 5:1 ratio K is low only if the smaller spheres comprise less than 30% of the mixture.

Flow Theory Based on the Shape of the Solid Constituents

The flow of fluids through unconsolidated beds may be related to the motion of a single spherical particle in an infinite fluid by means of a resistance coefficient (ψ) and the Reynolds number (Re).

$$\psi_s = \frac{F}{\rho \bar{u}^2} \quad \text{---(3)}$$

where F = resistance force per unit projected area

$\bar{u}$ = relative velocity

ρ = density of fluid

$$Re = \frac{d \bar{u} \rho}{\mu} \quad \text{---(4)}$$

where d = diameter of sphere

μ = absolute viscosity

Values of ψ_R are plotted in Figure 2 for beds of spherical particles.

$$(\psi_s = 0.0256 \psi_R)$$

At Re less than approximately 1.0, $\psi_s = \frac{12}{Re}$ for a single spherical particle. Substitution into equations 3,4 yields the equation for the viscous resistance to the motion of a single spherical particle in an infinite fluid (Stokes' law).²⁵

$$F_T = 3\pi d \bar{u} \mu \quad \text{---(5)}$$

By applying Stokes' law to a granular porous mass¹¹ or by dimensional analysis featuring a length characteristic of the solid constituents,²² the resistance coefficient and the Reynolds number may be expressed as follows for the horizontal flow of an incompressible fluid through a granular porous mass.

$$\psi = g_{cL} \frac{\Delta P}{L} \frac{d}{u^2} \frac{1}{\rho_f} \frac{1}{F(k)} \frac{1}{F(\epsilon)} \frac{1}{F(w)} \quad \text{---(6)}$$

Resistance Coeff. c_R Test

$$Re = \frac{du \rho_f}{\mu} \quad \text{---(7)}$$

where $\frac{\Delta P}{L}$ = pressure gradient in direction of superficial velocity

u = superficial velocity

ρ_f = density of incompressible fluid

d = a length characteristic of the solid constituents

= diameter for spherical particles, equivalent diameter for non-spherical

$F(k)$ = a function expressing the effect of the shape of the particles. Numerically, it is the ratio of the pressure drop of a mass of non-spherical particles to that of uniform spherical ones. Equals 1.0 for spheres.

$F(\epsilon)$ = a porosity function

$F(w)$ = a wall effect function. Numerically, it is the ratio of the pressure drop of a mass of finite cross-section to that of a mass of infinite cross-section. Where D/d exceeds 50, $F(w)$ = approx. unity. (D = diameter of container)

For mixtures of spheres,

$$d = \left[\frac{\sum N_i d_i^2}{\sum N_i} \right]^{1/2} \quad \text{---(8)}$$

where d = mean surface diameter

and N_i = number of particles of size d_i

d_i = diameter of particle

It may be noted that the form of the resistance coefficient expressed by equation (6) is the same as that for a circular pipe when all functions F equal unity.

$$\psi = g_c \frac{\Delta P}{L_p} \frac{d_p}{\rho_f u^2} \quad \text{---(9)}$$

$$Re = \frac{u d_p \rho_f}{\mu} \quad \text{---(10)}$$

where u = average velocity in the pipe

Sub p = pipe

Since $F(k)$ and $F(w)$ are equal to unity for the experimental region concerned herein (spherical particles and D/d exceeds 50), only $F(\epsilon)$ is considered further. The effect of porosity on the resistance to flow is great as may be deduced from the plot of $F(\epsilon)$ vs. ϵ in Figure 3. The practice is to express the porosity function in reference to the value of the function at $\epsilon = 0.4$. Several forms of the porosity function have been proposed.

The Blake-Carman Function.

$$F^{BC}(\epsilon) = \frac{1}{5.625} \frac{(1-\epsilon)^2}{\epsilon^3} \quad \text{--- (11)}$$

This function applies in the laminar region and has been tested by Carman⁶ for spherical and non-spherical particles in the porosity range 0.26 to 0.89. Coulson⁸ reported that the function is independent of the shape in the case of identical non-spherical particles of the types shown in Figure 1. However, he found that the Rose function (see below) was more accurate in the case of plates.

The Fair-Hatch Function.¹⁰

$$F^{FH}(\epsilon) = c \frac{(1-\epsilon)^{3-n}}{\epsilon^3} \quad \text{--- (12)}$$

where c = constant

n = 1 for laminar flow, 2 for fully turbulent.

The Rose Function.

A function independent of particle shape has been determined by Rose^{21,22} for spherical and non-spherical particles in the range of porosity from 0.37 to 0.92. This function, which is plotted in Figure 3, applies over the laminar region and into the transition regions.

FIGURE 5
Porosity Functions

- 1. FLANK-GIRTH
- 2. ROSE
- 3. CROOKER-HUI
- 4. FELLING

Porosity Function $F(c)$ Relative to $F(0.1)$

3.0

2.0

1.0

0

0.3

0.4

0.5

0.6

0.7

0.8

Concentration (c)

The Grootenhuis Function.

$$F^G(\epsilon) = \frac{2.39(1-\epsilon)^{3.5}}{\epsilon} \quad \text{--- (13)}$$

This is an attempt at a mathematical expression for the Rose function, and agrees satisfactorily with it over the range shown in Figure 3.

The Fehling Function.¹¹

$$F^F(\epsilon) = \frac{0.0256}{\epsilon^4} \quad \text{--- (14)}$$

This expression has been applied over a range of Re from 20 to 250 and ϵ from 0.366 to 0.398.

Flow Theory Based on the Flow Characteristics of Porous Masses

This theory is based on flow characteristics rather than the structural characteristics (pore or particle parameters) used in the previous sections. The flow parameters may be derived from the resistance coefficient: Reynolds number relationship described in the previous section.

In the laminar region

$$\psi = \frac{A'}{Re} \quad \text{--- (15)}$$

where $A' =$ a constant

By substitution from equation (6), (7)

$$\frac{\Delta P}{L} = \frac{A' F(k) F(\epsilon) F(w)}{g_c d^2} u \mu \quad \text{--- (16)}$$

Since in this flow region the functions F are independent of Re ,

$$\frac{\Delta P}{L} = \frac{1}{\alpha g_c} u \mu \quad \text{--- (17)}$$

where $\alpha =$ permeability, a property of a particular porous mass, (ft^2). Equation (17) is known as the d'Arcy equation of flow through porous masses. Ruth²³ uses the equation

$$\frac{\Delta P}{L} = u \mu \alpha' \rho / g_c \quad \text{--- (18)}$$

where $\alpha' =$ specific cake resistance (ft/lb m)

$\rho_c =$ density of the cake

By comparing equations (18), (17)

$$\alpha' \rho_c = \frac{1}{\alpha} \quad \text{--- (19)}$$

Brownell and Katz⁴ define $k (= \alpha g_c)$ as

$$k = \frac{d^2 F_{Re}}{32 F_f} \cdot g_c \quad \text{--- (20)}$$

where F_{Re} is a function of the porosity, the diameter of the particles, the sphericity or shape of the particles, the orientation of the particles and their roughness.

F_f is a friction-factor factor which is a function of the same variables as F_{Re} .

F_{Re} and F_f are obtained by empirical methods and are presented as charts in terms of the variables sphericity and porosity.

By comparison with equation (24) below it is observed that

$$\frac{F_{Re}}{32 F_f} = \frac{1}{\psi \cdot R_e F(k) F(\epsilon) F(w)} \quad \text{--- (21)}$$

Useful relationships may be derived relating the permeability (α), the porosity (ϵ), and the coefficient of resistance (ψ).

For example, from equations (17), (2)

$$\alpha = \frac{\epsilon^3}{(1-\epsilon)^2 S_o^2 K} \quad \text{--- (22)}$$

For spherical particles $S_o = \frac{6}{d}$, $K = 5.0$, and equation (18) becomes

$$\alpha = \frac{d^2}{180} \frac{\epsilon^3}{(1-\epsilon)^2} \quad \text{--- (23)}$$

Also, from equations (15), (16), (17)

$$\alpha = \frac{d^2}{\psi \cdot R_e F(k) F(\epsilon) F(w)} \quad \text{--- (24)}$$

For spherical particles in the laminar region equation (24) becomes

$$\alpha = \frac{d^2}{1000 F(\epsilon) F(w)} \quad \text{--- (25)}$$

since $\psi = \frac{1000}{R_e}$ in this region (see Figure 2) and $F(k) = 1$ for spherical particles.

Physical properties of the liquid such as viscosity and surface tension do not appear to affect permeability in the laminar region.¹⁴ End effects may be important in the flow of fluids through pipes. However, in the case of flow through porous masses composed of spherical particles it has been shown that end effects are negligible even when the porous mass is as little as 10 particle diameters thick.²¹

The foregoing relationships for the flow of incompressible fluids through porous masses have received broad application in filtration calculations.

Application to Centrifugal Filtration

The application of the foregoing filtration equations to filtration in a basket-type centrifugal filter, wherein the driving force ΔP is supplied by centrifugal action on the liquid, bears a two-fold complication: The algebraic expression of the driving force corresponding to ΔP and the value of the permeability. Modifications of the filtration equations for the centrifugal case have been proposed by Maloney,¹⁸ Smith,²⁴ Burak and Storrow,⁵ Inglesent and Storrow,¹⁶ and Grace.¹² Grace shows that in general the permeability of the cake in centrifugal filtration changes throughout its depth because it, like the liquid, is subjected to centrifugal force of which the magnitude depends on the radius of rotation.

$$\text{Gees} = 2.84 \times 10^{-5} (\text{RPM})^2 r \quad - - - - - (26)$$

where Gees = centrifugal force, measured in gravities

r = radius (in.)

Grace therefore concludes that compression - permeability data taken on compressed static beds¹³ are, in general, not applicable to the calculations of flow rates in centrifugal filtration. Oyama and Sumikawa²⁰ find the specific resistance of cakes of 1-50 micron diatomaceous earth and silica

powder to be 1.5 and 3 times as great, respectively, for centrifugal filtration as for constant pressure filtration. They attribute the increase to a migration of fines to the surface of the cake in the centrifugal filter. Haruni and Storow,¹⁵ on the other hand, are able to calculate the necessary filtration constants from a compressed static bed and show reasonable agreement with data obtained on a laboratory centrifugal. In cases where the cake is incompressible and uniform the problem of the changing filtration constant disappears.

The Burak-Storow and Grace equations have been supported by experimental data and should be considered in detail.

Burak-Storow Equation.

$$Q_s = \frac{4\pi^3 N^2 h K_c (r_o^2 - r_f^2)}{\mu g \ln \frac{r_o}{r_c}} \quad \text{--- (27)}$$

where Q_s = volumetric flow rate through cake
 N = revolutions per second
 h = depth of basket parallel to axis
 K_c = average cake permeability (lb m/sec²)
 r_o = radius to inside of filter medium
 r_f = radius to surface of liquid
 μ = absolute viscosity of filtrate
 g = acceleration in gravitational field
 r_c = radius to surface of cake

Grace Equation for Incompressible Cakes.

$$Q_T = \frac{4\pi^3 N^2 \rho_f h (r_o^2 - r_f^2)}{\mu \left[\rho_s \alpha' (1 - \epsilon) \ln \frac{r_o}{r_c} + \frac{R_m}{r_o} \right]} \quad \text{--- (28)}$$

where Q_T = volumetric flow rate through cake and medium
 ρ_f = density of filtrate

ρ_s = density of solids comprising cake

R_m = filter medium resistance

α' = average specific cake resistance (ft/lb)

Grace shows that equation (28) may be written in the form

$$Q_T = \frac{\Delta P' g_c}{\mu \left[\frac{\alpha' W}{A_{lm} \cdot A_m} + \frac{R_m}{A_c} \right]} \quad \text{--- (29)}$$

where $\Delta P' = \frac{(2\pi N)^2 \rho_f (r_o^2 - r_f^2)}{2g_c} \quad \text{--- (30)}$

where $\Delta P'$ = over-all hydraulic driving force causing flow through cake in centrifugal filtration

W = total weight of solids in cake

A_{lm} = log mean area of cake perpendicular to flow

A_m = arithmetic average area of cake perpendicular to flow

A_c = area of cloth

By taking $A_{lm} \cdot A_m = A^2$, substituting from equation (19), and neglecting R_m , equation (29) becomes identical with equation (17), the d'Arcy equation, which applies to the laminar region. This is appropriate because as a rule centrifugal filtrations fall in the laminar flow region which is seen from Figure 2 to extend to values of the Reynolds number as great as approximately 2.

By comparing equations (27) and (28), and substituting from equation (19),

$$K_c = \frac{\rho_f g}{\rho_s \alpha' (1 - \epsilon)} = \rho_f \alpha g \quad \text{--- (31)}$$

The relationships which have been reviewed and derived in this Chapter will be applied in a later Chapter to correlate new data reported herein for the flow of incompressible fluids through porous beds of spheres of mixed sizes in centrifugal filters.

CHAPTER II

Equipment, Method of Operation, Materials

Two perforated baskets for centrifugal filtration were mounted horizontally on individual drive shafts. By means of a variable speed drive and two sets of pulleys it was possible to drive either basket over the approximate ranges 300-1000 and 1200-4000 rpm. Thus, in the 5 in. diameter smaller basket and in the 11 in. diameter larger basket, it was possible to develop maximum centrifugal forces of approximately 1140 and 2500 gees, respectively (equation 26). RPM measurements were made with a Stroboscope.

The equipment layout may be seen in Figures 4 and 5. The front covers are removed to reveal the baskets.

Water or other filtrate was run into the small basket through a spray nozzle and into the large basket through a wing tip. Water was taken from the Baton Rouge city main and other filtrates were supplies by means of a centrifugal pump and storage tank. Flow rates were regulated through a hand-operated needle valve.

Dimensions and operating ranges are given in Table I for both baskets.

From the dimensions given in Table I and equation 30 the maximum driving force for the filtration of water through porous beds is calculated to be approximately 13 psi for the small bowl and 93 psi for the large bowl. Thus, on this laboratory installation it is possible to cover the

FIGURE 4
Equipment Layout

Plate I

Equipment Arrangement

Plate II

Drive Assembly

Plate III

Large Basket, Mounted

FIGURE 5

Large Basket, Disassembled

Plate IV

Large Basket, Dismounted

TABLE I

Dimensions and Operating Ranges of
Experimental Centrifugal Filters

	<u>Small Basket</u>	<u>Large Basket</u>
Diameter D (in.)	5	11
Radius to inside of cloth r_o (in.)	2.303	5.187
Liquid Levels r_f (in.)		
Level 1	1.937	3.938
Level 2	2.047	4.469
Radius to cake surface r_c (in.)	As required	As required
Depth of basket h(in.)	1.125	2.125
RPM Range	300-1000	300-1000
	1200-4000	1200-4000
Maximum Gees	1140	2500
Maximum total hydraulic driving force for filtration (water) $\Delta P'$ (lb f/in. ²)	13	93

range of Gees and ΔP existing in normal commercial operation. For example, a 40 in. diameter commercial machine operating at 800 rpm and a liquid depth of 6 in. would develop 364 Gees at the basket wall and a total hydraulic driving force of 67 psi.

Cloth, supported by coarse wire mesh, served as the septum. Putty and caulking were forced into seals at both the back and the front of the basket to prevent leaks of filtrate around the ends of the cake. It was possible to make several runs with one cloth.

Method of Operation and Materials

Cake was deposited by spooning dry solids into a pool of liquid in the rotating basket. The mass of cake used for the small bowl was 10, 20, or 25 grams whereas 300-450 grams were used in the large machine. In the case of the small bowl, the cake was deposited in approximately 1 gram increments whereas the increments were 5-10 grams for the large bowl. Depositing the cake in this manner simulates the actual formation of a cake when slurry is fed and there is a liquid level above the cake. Any effect of classification is minimized by addition in many increments. A liquid level was maintained above the cake at all times during a run.

The rate of flow of filtrate was measured at two liquid levels and over a range of rpm for each cake deposited as above. Immediately before each cake run the rate of flow of filtrate through the septum was measured at the same two liquid levels. Figure 6 shows the data taken in run 5. Other data are tabulated in Appendix A.

Styrene-divinyl benzene spheres supplied by the Dow Chemical Co., Midland, Michigan, comprised the cakes. Four mesh ranges were used: 50/100, 100/200, 200/400, and 400/-. Photomicrographs of these materials and the fines contained in them are shown in Figures 7 and 8.

Photomicrographs of Styrene-Divinylbenzene Spheres

Plate V

50/100 Mesh

Plate VI

100/200 Mesh

Plate VII

200/400 Mesh

Plate VIII

400/- Mesh

FIGURE 8

Photomicrographs of Styrene-Divinyl Benzene Spheres

Plate IX

200/400 Mesh

Plate X

Fines from 200/400 Mesh

Plate XI

Electronmicrograph. Fines from 200/400 Mesh

Bulk densities taken on samples settled by tapping and true densities by the water displacement method are given in Table II.

TABLE II
Densities of Styrene-Divinyl Benzene Spheres

<u>Mesh</u>	<u>Bulk Density</u> <u>ρ_c (lb/ft³)</u>	<u>True Density</u> <u>ρ_s (lb/ft³)</u>
50/100	40.2	66.1
100/200	40.8	65.7
200/400	40.4	66.6
400/-	40.2	66.4
Average	40.4 $\pm$ 0.2	66.2 $\pm$ 0.3

The particle size analyses by microscopic measurement and the mean surface diameters calculated therefrom are given in Table III. The size of aggregates was taken by Martin's method.³

TABLE III

Particle Size Analyses of Styrene-Divinyl Benzene Spheres

Scales*	Number of Particles in Mesh Range			
	<u>50/100</u>	<u>100/200</u>	<u>200/400</u>	<u>400/-</u>
0.1			15	6
0.2		2	40	40
0.3	1	16	60	50
0.4	1	70	72	49
0.5	1	89	80	32
0.6	2	93	48	18
0.7	3	88	23	12
0.8	6	78	12	14
0.9	12	62	8	20
1.0	20	43	19	28
1.1	28	16	10	16
1.2	40	7	4	6
1.3	48	3	1	1
1.4	52	2		
1.5	48			
1.6	34			
1.7	22			
1.8	16			
1.9	10			
2.0	5			
2.1	3			
2.2	3			
2.3	2			
2.4	1			
2.5	1			
2.6	1			
2.7	1			
2.8	1			
<hr/>				
Total Particles Measured	352	569	392	292
$D_{av}(ft)$ (ultimate particles)	6.89×10^{-4}	3.20×10^{-4}	2.21×10^{-4}	1.12×10^{-4}
Average of Screens (ft)	5.75×10^{-4}	3.42×10^{-4}	1.68×10^{-4}	1.12×10^{-4}
d , Surface Mean Diameter (ft)				
By Equation (8)	7.08×10^{-4}	3.54×10^{-4}	2.73×10^{-4}	3.12×10^{-4}

* One scale = 0.15 mm

An analysis of the water used in these filtration experiments is given in Table IV.

TABLE IV
Analysis of Baton Rouge City Water*

<u>Component</u>	<u>ppm</u>
SiO ₂	24.0
Fe	0.02
Ca	1.0
Mg	0.04
Na	97.0
K	3.0
CO ₃ ⁼	36.0
HCO ₃ ⁻	173.0
SO ₄ ⁼	11.0
Cl ⁻	6.1
NO ₃ ⁻	0.2
Total dissolved solids	260
Total Hardness, CaCO ₃ , Soap Test	0

* Analysis supplied by Baton Rouge Water Works Company.

CHAPTER III

Discussion and Correlation of Results

Resistance coefficients (ψ) and permeabilities (α , ft²) are calculated for the filtration data taken on the styrene-divinyl benzene spheres. Several factors of the Burak-Storrow and Grace equations are checked. Centrifugal filtration data are correlated by means of the Burak-Storrow and Grace applications of the d'Arcy equation, and by a dimensionless form of the same equation.

Resistance Coefficients and Permeabilities

Calculated values of the resistance coefficient and the permeability are listed in Appendix B. For these calculations, where the RPM at which the data were taken for the flow rate through the medium only (Q_m) did not coincide with the RPM at which the data were taken for the flow rate through the medium and the cake (Q_T), values for Q_m were taken from a plot such as Figure 6. The resistance coefficients are plotted in Figures 9, 10, 11, and 12. The average permeability for each run was calculated from points read from straight-line plots of the type illustrated in Figure 6. The averages for each mesh size and their standard deviations are listed in Table V as well as values of permeability calculated from equation (23).

The slopes of approximately -1 for ψ vs Re are anticipated because for any of the experimental runs ψ is theoretically proportional to $\frac{1}{U}$ and Re is proportional to u . The deviations, run to run, and the large

RESISTANCE COEFFICIENTS FOR SOLID BODIES
STRIKING DIVING HELICOPTER

Reynolds Number Re

0.001

0.01

0.1

1.0

TABLE V

Experimental and Calculated Permeabilities
of Styrene-Divinyl Benzene Spheres

<u>Mesh</u>	$\frac{d}{(ft) \times 10^4}$	$\frac{\Delta_{exp.}}{(ft^2) \times 10^{13}}$	$\frac{\Delta_{calc.}^{13}}{(ft^2) \times 10^{13}}$
50/100	7.08	19.1 ± 7.6	4440
100/200	3.54	6.1 ± 1.1	1110
200/400*	2.73	6.9 ± 1.1	660
400/- **	3.12	9.3 ± 2.1	862

* Excluding run 13

** Excluding run 25

difference between observed and calculated values of the permeability are attributed to the fines or possibly to gas blocking. The fines could not be taken into account in the calculations because of the probable variation in fines content of the cake from run to run, the impossibility of measuring the thickness of any layer of fines which might have formed, and the practical difficulty of calculating the thickness of such a layer with sufficient accuracy. However, the experimental permeabilities may be used to correlate the filtration rates, as discussed in a later section.

Check of Factors of Burak-Storow and Grace Equations

The Grace form will be used to illustrate the applicability of the Burak-Storow and Grace equations.

$$Q_T = \frac{4\pi^3 N^2 \rho_f h (r_o^2 - r_f^2)}{\mu \left[\rho_s \alpha' (1 - \epsilon) \ln \frac{r_o}{r_c} + \frac{R_m}{r_o} \right]} \quad (\text{equation 28})$$

Equation (28) may be written as

$$\frac{1}{Q_T} = \frac{1}{Q_s} + \frac{1}{Q_m} \quad \text{-----} \quad (32)$$

Effect of RPM (N) on Flow Rate

From equation (28) and (32), when N is the only independent variable,

$$Q_T = C^I N^2 \quad \text{-----} \quad (33)$$

$$Q_s = C^{II} N^2 \quad \text{-----} \quad (34)$$

$$Q_m = C^{III} N^2 \quad \text{-----} \quad (35)$$

where C^I , C^{II} , C^{III} are constants.

Experimental values of Q_T and Q_m are plotted in Figure 13 showing a typical check of equations (33), (35). When equations (33) and (35) are satisfied, equation (34) is automatically satisfied and the plot for Q_s may be established by projecting a straight line through the origin and one value of Q_s calculated from equation (32).

Effect of Liquid Depth on Flow Rate

From equation (28), when r_f and N are the independent variables,

$$Q_T = C^{1V} N^2 (r_o^2 - r_f^2) \quad \text{--- (36)}$$

$$Q_m = C^V N^2 (r_o^2 - r_f^2) \quad \text{--- (37)}$$

where C^{1V} and C^V are constants.

A test of equation (36) is given in Figure 14 using data from run 20. The straight-line plots obtained for both Q_T and Q_m at both liquid levels check equations (36) and (37).

Effect of Viscosity on Flow Rate

From equation (28), when μ and N are the independent variables,

$$Q_T = \frac{C^{V1} N^2}{\mu} \quad \text{--- (38)}$$

where C^{V1} is a constant.

The data contained herein are not suitable for testing equation (38) because of the small differences in viscosity in most of the runs and a change in cake structure during run 25 (glycerol-water solution).

Effect of Cake Depth on Flow Rate

From equation (28), when N and r_c are the independent variables,

$$Q_T = \frac{C^{V11} N^2}{\ln \frac{r_o}{r_c}} \quad \text{--- (39)}$$

where C^{V11} is a constant.

Data from runs 17 and 21, having the same cake structure (same α), are used to check equation (39), in Figure 15. It is seen that equation (39) is satisfied, within the accuracy of the data.

Correlation of Data

Correlation by Burak-Storrow and Grace Equations.

It is concluded from the foregoing tests that the data reported herein, where applicable, check the form of the centrifugal-filtration

FIGURE 15
Effect of Core Depth on Centrifugal Flow Rate

equations by Burak and Storrow and Grace. This conclusion is illustrated by Figure 16 in which the experimental flow rate through solids only (Q_s) is plotted for the four sizes of spheres used as cakes. Average permeabilities calculated from the data in Appendix B are used to plot the lines for the styrene-divinyl benzene spheres. Grace and Haruni-Storrow data which are calculated from data in their articles,^{12,15} are also plotted in Figure 16. Chalk (Haruni-Storrow) and the styrene-divinyl benzene spheres form incompressible cakes whereas the G-60 Darco (Grace) forms a compressible cake. For the latter case, α is calculated from α' determined by Grace¹⁵ and is plotted as a function of $\Delta P'$ in Figure 17.

Correlation by Dimensionless Form of d'Arcy Equation

The dimensionless form of the d'Arcy equation may be derived as follows.

$$\frac{\Delta P'}{L} = \frac{u\mu}{\alpha g_c} \quad (\text{d'Arcy, equation 1'})$$

For a centrifugal filter

$$\Delta P' = \frac{a}{g_c} \rho_f H \quad \text{--- (40)}$$

where a = acceleration in the centrifugal field

H = the depth of the liquid

$$a = \omega^2 r_{av} = (2\pi N)^2 r_{av} \quad \text{--- (41)}$$

where ω = angular acceleration

r_{av} = radius to average depth of liquid

$$H = \frac{\text{Volume}}{\text{Area}} = \frac{(r_o^2 - r_f^2)}{2 r_{av}} \quad \text{--- (42)}$$

Substitution of equations (41) and (42) into equation (40)

yields

$$\Delta P' = \frac{(2\pi N)^2}{2g_c} \frac{\rho_f (r_o^2 - r_f^2)}{r_{av}} \quad \text{--- (43)}$$

FIGURE 16

Application of Borch-Storow and Grace
Forms of Centrifugal Filtration Equation

Mash Size	$\alpha \times 10^{13}$ ($g \cdot l^{-1}$)
Styrene-DVB Spheres	
50/100	18.1 $\pm$ 0.6
100/200	6.1 $\pm$ 1.1
200/400	6.9 $\pm$ 1.1
400/-	0.3 $\pm$ 2.1

$$\text{Slope} = \alpha = \frac{1}{\rho_{\text{max}}(1-e)} = \frac{K_c}{A_{\text{th}}}$$

- ① 5 Lb Chalk Cake, Warren and Storow^{1,5}
- ② 0.89 lb 0-60 Darco, Grace^{1,2}

$$\frac{4\pi^2 H^2 \rho_m (r_o^2 - r_i^2)}{\mu \ln \frac{r_o}{r_i}} \left(\frac{g}{\text{sec}} \right) \times 10^{-6}$$

100

FIGURE 17

PERMEABILITY OF 0-60 DARGO

(CALC. FROM DATA BY GRAVES¹⁵)

$F_{1.01} (ML^2) \times 10^{12}$

10

100

p (psi)

Substituting equation (43) into equation (17) and noting that $u = \frac{Q_s}{A}$ leads to

$$\frac{Q_s}{A} = \frac{\alpha (2\pi N)^2 \rho_f (r_o^2 - r_f^2)}{2\mu L} \quad (44)$$

On rearranging, a dimensionless form of the d'Arcy equation is obtained for centrifugal filtration.

$$\frac{Q_s L}{\alpha A N} = \frac{2\pi^2 N \rho_f (r_o^2 - r_f^2)}{\mu} \quad (45)$$

The area may be substituted by

$$A = 2\pi r_{lm} h \quad (46)$$

where r_{lm} = log mean radius

This leads to an equivalent dimensionless form

$$\frac{Q_s \ln \frac{r_o}{r_c}}{\alpha N h} = \frac{4\pi^3 N \rho_f (r_o^2 - r_f^2)}{\mu} \quad (47)$$

When the resistance of the medium to flow is included as R_m (ft^{-1}), equation (45) becomes

$$\frac{Q_s \left[\frac{L}{\alpha} + R_m \right]}{A N} = \frac{2\pi^2 N \rho_f (r_o^2 - r_f^2)}{\mu} \quad (48)$$

And equation (47) becomes

$$\frac{Q_s \left[\frac{1}{\alpha} + \frac{R_m}{L} \right] \ln \frac{r_o}{r_c}}{N h} = \frac{4\pi^3 N \rho_f (r_o^2 - r_f^2)}{\mu} \quad (49)$$

It may be noted that the Burak-Storow and Grace equations may be obtained by substitution of equations (46) and (31) into equation (44).

Application of the dimensionless form of the centrifugal filtration equation is illustrated in Figure 18 by data from this work and from the literature.^{12,15}

FIGURE 1B

Dimensionless Form
of Centrifugal Filtration Equation

Styrag-DVB Spheres

Mesh	Run	Symbol
50/100	4	○
100/200	10	□
200/400	15	△
400/-	22	▽
Darco G-10, Granite	15	◊
Chalk, Harco and Storck	15	◊

120

110

100

90

80

70

60

50

40

30

20

10

0

10

20

30

40

50

60

70

80

90

100

$\frac{P_0(r_0^2 - r_1^2)}{\mu} \times 10^{-10}$

$\frac{P_0(r_0^2 - r_1^2)}{\mu} \times 10^{-10}$

SUMMARY AND CONCLUSIONS

Centrifugal filtration data were taken in two laboratory centrifugals on four mesh sizes of styrene-divinyl benzene spheres. A much lower value of the permeability was obtained experimentally than would be predicted theoretically based on the average particle size, not including the fines. This discrepancy was speculated to have been caused by the fines or possibly by gas blocking of the cakes.

The experimental permeabilities were useful in correlating the data which, where applicable, were in agreement with the Burak-Storrow and Grace forms of the d'Arcy equation. Correlation by means of these relationships was illustrated.

A dimensionless form of the d'Arcy equation, applicable to centrifugal filtration, was derived. Its use was illustrated by the correlation of data obtained in the present work and data taken from the literature.

NOTATION

A'	constant
A_c	area of cloth
A_{lm}	log mean area
A_m	arithmetic average area
a	acceleration in centrifugal field
c	constant
d	diameter
F	degrees Fahrenheit
F_f	friction-factor factor
$F(k)$	a function expressing the effect of the shape of the particle in fluid flow
F_{Re}	Reynolds' number factor
$F(\epsilon)$	a function expressing the effect of the bed porosity in fluid flow
$F(w)$	wall effect function in fluid flow
g_c	conversion factor 32.2 lb mass/lb force -ft/sec ²
h	depth of centrifugal basket parallel to the axis
K	Kozeny filtration constant
k	permeability (Brownell and Katz)
L	depth of bed in direction of flow
N_i	number of particles
N	rate of rotation of centrifugal basket

P	pressure
Q_m	filtrate flow rate through medium only
Q_s	filtrate flow rate through solids only
Q_T	filtrate flow rate through medium and cake
Re	Reynolds' number
R_m	filter medium resistance
r	radius
r_c	radius to surface of cake
r_f	radius to surface of fluid
r_o	radius to inside of filter medium
S_o	surface area/unit volume of particles
u	velocity
W	weight of solids in cake

α	permeability (ft ²)
α'	specific resistance (ft/lb)
Δ	finite change of variable
ϵ	porosity
μ	absolute viscosity
ρ_c	bulk density of cake
ρ_s	true density of solids
ψ_R	Rose resistance coefficient
ψ_s	resistance coefficient for single particle
ω	angular acceleration

sub p	pipe
sub f	fluid
sub s	solids

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APPENDIX A

Centrifugal Filtration Data for Styrene-Divinyl Benzene Spheres

Run No.	Filtrate* Temp. (F)	r _c (in.)	Q _m or Q _T (ml/min)	N (RPM)	Q(ml/min)					
					r _f = 1.937 in.	r _f = 2.047 in.				
50/100 Mesh										
1	81.5	2.191	Q _m	2510	464	318				
				2160	344	203				
				1770	202	129				
				2540	474	304				
			Q _T	1710	131	91				
				2100	183	127				
				2500	258	213				
				2850	380	244				
				2	81.5	2.184	Q _m	2870	632	464
								2510	478	318
2120	325	189								
1720	187	142								
Q _T	1720	117	75							
	2120	199	110							
	2500	276	154							
	2860	345	165							
	3	81	2.070				Q _m	740	180	133
								1580	1070	856
1700				—	1065					
1350				794	663					
Q _T				1350	230	180				
				1880	558	402				
				1630	415	322				
				4	83	2.156	Q _m	3280	930	624
								2775	687	479
								2245	507	330
1700	307	188								
Q _T	1700	179	103							
	2250	308	198							
	2760	400	262							
	3280	478	270							

* Filtrate is Baton Rouge city water unless otherwise specified.

Centrifugal Filtration Data for
Styrene-Divinyl Benzene Spheres
(Continued)

Run No.	Filtrate* Temp. (F)	r_c (in.)	Q_m or Q_T (ml/min)	N (RPM)	Q (ml/min)					
					$r_f = 1.937$ in.	$r_f = 2.047$ in.				
50/100 Mesh (Continued)										
5	84	2.223	Q_m	3350	456	275				
				2850	354	191				
				2320	223	140				
				1700	129	75				
			Q_T	1700	91	62				
				2250	166	90				
				2710	247	166				
				3280	355	219				
				3810	523	306				
									$r_f = 3.938$ in.	$r_f = 4.469$ in.
6	81	4.554	Q_m	2390	4637	3046				
				2000	3500	2091				
				1620	2182	1455				
				1310	1500	1000				
			Q_T	1310	955	636				
				1630	1364	909				
				2010	2091	1318				
				2400	2819	1773				
									$r_f = 1.937$ in.	$r_f = 2.047$ in.
				100/200 Mesh						
7	81.5	2.188	Q_m	3230	760	482				
				2870	575	400				
				2515	418	274				
				2120	283	184				
				1730	188	121				
				1730	120	65				
			Q_T	2120	163	73				
				2510	228	131				
				2880	278	113				
				2510	—	129				
3225	555	289								

* Filtrate is Baton Rouge city water unless otherwise specified.

Centrifugal Filtration Data for
Styrene-Divinyl Benzene Spheres
(Continued)

Run	Filtrate*		Q_m or Q_T	N	Q (ml/min)	
No.	Temp. (F)	r_c (in.)	(ml/min)	(RPM)	$r_f = 1.937$ in.	$r_f = 2.047$ in.
100/200 Mesh (Continued)						
8	82	2.183	Q_m	2310	622	492
				2520	607	313
				2140	322	205
				1740	237	171
			Q_T	1740	115	55
				2140	120	84
				2520	212	105
				2890	323	179
9	84	2.164	Q_m	3280	449	249
				2780	347	200
				2250	213	119
				1710	129	87
			Q_T	1710	97	67
				2260	144	94
				2770	233	131
				3300	272	174
10	82	2.164	Q_m	3010	1074	707
				2490	755	444
				1950	452	279
				1710	347	190
			Q_T	1710	129	74
				2110	184	102
				2500	278	151
				3020	469	271
11	84.5	2.196	Q_m	1330	133	109
			Q_T	1330	62	72
12	84.5	2.185	Q_m	1600	84	109
			Q_T	1600	57	67
23	76	2.195	Q_m	2000	183	137
			Q_T	2000	102	82
24	76	2.196	Q_m	2330	143	95
			Q_T	2330	90	65

* Filtrate is Baton Rouge city water unless otherwise specified.

Centrifugal Filtration Data for
Styrene-Divinyl Benzene Spheres
(Continued)

Run	Filtrate*		Q _m or Q _T	N	Q(ml/min)	
No.	Temp. (F)	r _c (in.)	(ml/min)	(RPM)	r _f = 1.937 in.	r _f = 2.047 in.
200/400 Mesh						
13	81.5	2.195	Q _m	2880	471	308
				2520	360	241
				2140	246	180
				1740	178	100
			Q _T	1740	24	—
				2140	48	21
				2520	87	40
14	81	2.188	Q _m	2800	—	1072
				2260	873	698
				1720	477	360
				Q _T	1720	183
			2270	395	298	
			2800	675	523	
			3310	1059	780	
15	81.5	2.230	Q _m	3300	—	685
				2800	670	525
				2270	445	306
				1720	241	187
			Q _T	1720	128	85
				2270	281	198
				2800	433	290
				3310	491	420
				2790	345	—
					r _f = 3.938 in.	r _f = 4.469 in.
16	79.5	4.651	Q _m	2500	2773	1591
				2120	1682	1091
				1730	1182	773
				1360	773	5000
				2120	1682	—
			Q _T	1360	350	182
				1750	632	268
				2140	1141	573
				2520	1955	—

* Filtrate is Baton Rouge city water unless otherwise specified.

Centrifugal Filtration Data for
Styrene-DivinyI Benzene Spheres
(Continued)

Run	Filtrate*		Q_m or Q_T	N	$Q(\text{ml/min})$	
No.	Temp. (F)	$r_c(\text{in.})$	(ml/min)	(RPM)	$r_f = 1.937 \text{ in.}$	$r_f = 2.047 \text{ in.}$
200/400 Mesh (Continued)						
17	83	2.195	Q_m	2880	404	303
				2520	286	196
				2130	226	161
				1740	154	104
			Q_T	1740	92	62
				2140	134	73
				2520	176	103
				2880	300	164
400/- Mesh						
18	82	1.188	Q_m	2880	579	364
				2540	434	313
				2160	313	208
				1750	214	134
			Q_T	1760	130	98
				2150	223	134
				2530	294	214
				2890	466	264
19	79.5	2.230	Q_m	2870	436	289
				2540	313	207
				2150	212	128
				1750	123	89
			Q_T	2870	356	269
				1750	99	67
				2150	154	94
				2540	229	149
				2900	300	190
20	83	2.183	Q_m	3310	967	633
				2800	598	366
				2270	381	260
				1720	207	158
			Q_T	1720	142	109
				2280	269	183
				2800	397	285
				3300	559	386

* Filtrate is Baton Rouge city water unless otherwise specified.

Centrifugal Filtration Data for
Styrene-DivinyI Benzene Spheres
(Continued)

Run	Filtrate*		Q _m or Q _T	N	Q(ml/min)			
No.	Temp. (F)	r _c (in.)	(ml/min)	(RPM)	r _f = 1.937 in.	r _f = 2.047 in.		
400/- Mesh (Continued)								
21	83	2.234	Q _m	3270	—	392		
				2800	—	248		
				2270	240	174		
				1720	137	93		
				2270	237	—		
				2790	344	—		
				3300	537	412		
			Q _T	1720	147	—		
				2280	162	106		
				2800	256	176		
				1720	98	69		
				3300	421	259		
				r _f = 3.938 in.		r _f = 4.469 in.		
22	79.5	4.807	Q _m	2500	5235	—		
				2150	1655	986		
				1770	1127	659		
				1350	686	382		
			Q _T	1350	486	298		
				1540	632	377		
				1780	864	532		
				2010	1096	659		
				2240	1391	796		
				2410	1650	946		
				2550	2118	—		
				r _f = 1.937 in.		r _f = 2.047 in.		
				25	76**	2.177	Q _m	1340
1480	240	165						
1690	258	217						
1950	348	288						
2170	435	364						
2410	532	444						
Q _T	1340	102	87					
	1480	124	98					
	1690	146	132					
	1950	185	136					
	2170	213	175					
	2410	250	223					

* Filtrate is Baton Rouge city water unless otherwise specified.

** Filtrate is approximately 28% glycerol solution in water.
Specific Gravity = 1.062 at 76 F.

AT THE COURT OF THE

[illegible]

SEN. ROBERT F. D'AMICO

[illegible]

[illegible]

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
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APPENDIX C

Sample Calculations

Resistance Coefficient (ψ)

Run 4, point at 2760 rpm, $r_f = 2.047$ in. (See Appendix B)

$$\psi = g_c \frac{\Delta P_f}{L} \frac{d}{u^2 \rho_f} \frac{1}{F(\epsilon)} \quad (\text{equation 6})$$

$$Re = \frac{du \rho_f}{\mu} \quad (\text{equation 7})$$

$$\begin{aligned} \Delta P_f &= \frac{(2\pi N)^2 \rho_f (r_o^2 - r_f^2)}{2g_c} & (\text{equation 30}) \\ &= \frac{\left[2\pi \frac{2760}{60}\right]^2 (62.4) \frac{2.303^2 - 2.047^2}{144}}{2(32.2)} \end{aligned}$$

$$= 625 \text{ lb f/ft}^2$$

$$\begin{aligned} L &= r_o - r_c \\ &= \frac{2.303 - 2.156}{12} \end{aligned}$$

$$= 0.0123 \text{ ft}$$

$$d = 7.08 \times 10^{-4} \text{ ft} \quad (\text{Table III})$$

$$Q_s = \frac{Q_m Q_T}{Q_m - Q_T} \quad (\text{from equation 32})$$

$$= \frac{480 \times 262}{480 - 262} \frac{1}{28320 \times 60} = 3.40 \times 10^{-4} \text{ cfs.}$$

$$\begin{aligned} A &= \frac{2\pi(r_o + r_c)h}{2 \times 144} \\ &= \frac{2\pi(2.303 + 2.156)1.125}{2 \times 144} \end{aligned}$$

$$= 0.1093 \text{ sq ft}$$

Sample Calculations
(Continued)

$$u = \frac{Q_s}{A} = 3.11 \times 10^{-3} \text{ ft/sec}$$

$$F(\epsilon) = 1.1 \quad (\text{Figure 3})$$

$$\psi = 32.2 \frac{625}{0.0123} \frac{7.08 \times 10^{-4}}{(3.11 \times 10^{-3})^2} \frac{1}{62.4} \frac{1}{1.1}$$

$$= 1.76 \times 10^6$$

$$Re = \frac{(7.08 \times 10^{-4})(3.11 \times 10^{-3}) 62.4}{0.828(0.000672)}$$

$$= 0.246$$

Permeability (α)

$$\alpha = \frac{d^2}{\psi \cdot Re \cdot F(\epsilon)} \quad (\text{equation 24})$$

$$= \frac{(7.08 \times 10^{-4})^2}{(1.76 \times 10^6)(0.246) 1.1}$$

$$= 10.53 \times 10^{-13} \text{ ft}^2$$

Dimensionless Form of Centrifugal Filtration Equation

Run 22, point at 1780 rpm, $r_f = 3.938$ in. (See Appendix B)

$$\frac{Q_s \ln \frac{r_o}{r_c}}{\alpha N h} = \frac{4\pi^3 N \rho_f (r_o^2 - r_f^2)}{\mu} \quad (\text{equation 47})$$

$$\frac{Q_s \ln \frac{r_o}{r_c}}{\alpha N h} = \frac{\frac{4487}{28320 \times 60} \ln \frac{5.187}{4.807}}{10.1 \times 10^{-13} \frac{1780}{60} \frac{2.125}{12}} = 38.3 \times 10^6$$

$$\frac{N \rho_f (r_o^2 - r_f^2)}{\mu} = \frac{\frac{1780}{60} (62.4)(5.187^2 - 3.938^2) \frac{1}{144}}{0.866(0.000672)} = 25.2 \times 10^4$$

AUTOBIOGRAPHY

J. Byron Bingeman was born in South River, Ontario, Canada, on February 21, 1925. He attended grade schools in Waterloo County, Ontario, and High School in Kitchener, Ontario. In 1946 he graduated from Queen's University with the B.Sc. degree in Chemical Engineering. Graduate work at University of Detroit (1946-1948) and University of Minnesota (1948-1950) led to the M.S. degree in Physical Chemistry (1948) and the M.S. degree in Chemical Engineering (1950).

Since November, 1950, he has been employed in several Chemical Engineering capacities at Ethyl Corporation, Baton Rouge, Louisiana.

EXAMINATION AND THESIS REPORT

Candidate: J. Byron Bingeman

Major Field: Chemical Engineering

Title of Thesis: Centrifugal Filtration Through Beds of Small Spheres

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

May 6, 1957