ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

PULSED-BED APPROACH TO FLUIDIZATION

by

Masaru Kobayashi

Chemical Engineering Division

October 1969

A Dissertation Submitted to
The Graduate School of Northwestern University
in Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy
in the Field of Chemical Engineering

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
NOMENCLATURE	10
ABSTRACT	11
I. SUMMARY	11
II. INTRODUCTION (Statement of the Problem)	13
III. LITERATURE SURVEY	15
A. Pulsed-bed Studies	15
B. Heat-transfer Mechanism in Fluidized Beds	19
IV. EXPERIMENTAL APPARATUS, PROCEDURE, AND ANALYSIS	23
A. Apparatus	23
B. Material Used	26
C. Procedure and Analysis	26
1. Definition of Integral Gas Velocity and Pulsed-gas Velocity	26
2. Pressure Drops	27
3. Bed Expansion	27
4. Particle Velocity, Travel Distance, and Residence Time in Pulsed Beds	27
5. Residence Time in Fluidized Beds	30
6. Heat-transfer Coefficient	31
V. THEORETICAL DEVELOPMENT, EXPERIMENTAL RESULTS, AND DISCUSSION	33
A. Bed Behavior	33
1. Minimum Fluidization Velocity and Minimum Bubbling Velocity	33
2. Pressure-drop Patterns	33
3. Maximum Pressure Drops	36
4. Bed Expansion and Bed Movement	37
B. Mechanism for Heat Transfer from Wall to Gas-Solid Bed	43
1. Discussion of Models Proposed in the Literature	43
2. Proposed Model	45

TABLE OF CONTENTS

	<u>Page</u>
3. Discussion of Assumptions	48
4. Comparison of Proposed Model with Data.	48
C. Heat Transfer in Fluidized and Pulsed Beds	52
1. Effect of Particle Size and Pulsing Conditions.	52
2. Effect of Heater Position.	55
3. Effect of Static-bed Height.	56
4. Effect of Heater Length.	58
5. Effect of Physical and Thermal Properties of Particles and Gas	59
6. Estimation of Heat-transfer Coefficients in Pulsed Beds	62
VI. CONCLUSIONS	67
VII. SUGGESTIONS FOR FUTURE WORK.	68
APPENDIXES	
A. Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions.	69
B. Instantaneous Residence Time of Particles and Heat- transfer Coefficients in Fluidized Beds for 301- μ m Glass Beads with Static Bed Height = 6 in. and Surface Position = 3 in.	76
C. Bed Movements.	94
D. Experimental Data for Heat-transfer Coefficients	138
E. Instantaneous Particle Velocity and Residence Time in Pulsed Beds	146
ACKNOWLEDGMENTS	155
REFERENCES	156

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Flowsheet of Experimental Apparatus	23
2.	Pulsed-bed Column	24
3.	Internal Heater	25
4.	Illustration of Pulsed-gas Velocity and Integral Gas Velocity. .	27
5.	Method of Calculating Mean Residence Time.	29
6.	Some Patterns of Particle Motion in a Fluidized Bed	31
7.	Pressure-drop Patterns in a Pulsed Bed of 580- μ m Glass Beads for Pulsing Conditions Providing Good Particle-motion Characteristics	33
8.	Pressure-drop Patterns in a Pulsed Bed of 580- μ m Glass Beads Where On-periods Are Excessive for Maintaining Controlled Pulse Characteristics	34
9.	Pressure-drop Patterns in a Pulsed Bed of 580- μ m Glass Beads Where Off-period Is Too Long.	34
10.	Pressure-drop Patterns in a Pulsed Bed of 301- μ m Glass Beads	35
11.	Pressure-drop Patterns in a Pulsed Bed of 138- μ m Glass Beads for Pulsing Conditions Providing Good Particle-motion Characteristics	35
12.	Pressure-drop Patterns in a Pulsed Bed of 138- μ m Glass Beads Where Off-period Is Too Short	35
13.	Pressure-drop Patterns in a Pulsed Bed of 138- μ m Glass Beads Where On-period Is Too Long.	35
14.	Pressure-drop Patterns in a Pulsed Bed of 73- μ m Glass Beads with $v_0 = 0.0754$ ft/sec, On-period = 0.25 sec, and Off-period = 0.75 sec.	36
15.	Pressure-drop Patterns in a Pulsed Bed of 73- μ m Glass Beads with $v_0 = 0.0751$ ft/sec, On-period = 0.25 sec, and Off-period = 0.25 sec.	36
16.	Maximum Pressure Drops in Pulsed, Fluidized, and Packed Beds	37
17.	Bed-expansion Ratio vs Pulsed-gas Velocity for 580- μ m Glass Beads	38
18.	Bed-expansion Ratio vs Pulsed-gas Velocity for 301- μ m Glass Beads	38

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
19.	Bed-expansion Ratio vs Pulsed-gas Velocity for 138- μ m Glass Beads	38
20.	Bed Expansion at Various Frequencies vs Integral Gas Velocity	39
21.	Bed Expansion at Various Off-periods vs Integral Gas Velocity	39
22.	Bed Expansion at Various Ratios of On-period to Off-period vs Integral Gas Velocity	39
23.	Particle-velocity Profile at 6.0- and 1.5-in. Levels	40
24.	Bed Movement for 0.125-sec On-period, 0.375-sec Off-period, and 8-in. Bed Height.	42
25.	Bed Movement for 0.125-sec On-period, 0.375-sec Off-period, and 12-in. Bed Height.	42
26.	Bed Movement for 0.25-sec On-period, 0.25-sec Off-period, and 8-in. Bed Height.	42
27.	Bed Movement for 0.25-sec On-period, 0.25-sec Off-period, and 12-in. Bed Height.	42
28.	Comparison of Predicted Bed Stroke with Experimental Data	43
29.	Dependency of Effective Thermal Conductivity on Void Fraction.	44
30.	Illustration of Model.	46
31.	Rotation of Particles in Fluidized Bed.	48
32.	Comparison of Model with Data for Air-Glass-bead System. . .	49
33.	Comparison of Model with Data for Air-Copper-shot System. .	49
34.	Comparison of Model with Data for Helium-Glass-bead and Carbon Dioxide-Glass-bead Systems	49
35.	Instantaneous Residence Time of Particles in a Fluidized Bed.	50
36.	Comparison of Model with Data for 301- μ m Glass Beads.	51
37.	Comparison of Model with Data for 291- μ m Aluminum Shot. . .	52
38.	Heat-transfer Coefficients vs Gas Velocity for 580- μ m-diam Glass Beads and 0.5-in.-long Heater	52

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
39.	Heat-transfer Coefficients vs Gas Velocity for 301- μm -diam Glass Beads and 0.5-in.-long Heater	53
40.	Heat-transfer Coefficients vs Gas Velocity for 138- μm -diam Glass Beads and 0.5-in.-long Heater	54
41.	Heat-transfer Coefficients vs Gas Velocity for 73- μm -diam Glass Beads and 0.5-in.-long Heater	54
42.	Heat-transfer Coefficients vs Gas Velocity for 580- μm -diam Glass Beads and 2.0-in.-long Heater	54
43.	Heat-transfer Coefficients vs Gas Velocity for 580- μm -diam Glass Beads and 4.0-in.-long Heater	54
44.	Effect of Heater Position on Heat-transfer Coefficients in Fluidized Beds with 580- μm -diam Glass Beads and 0.5-in.-long Heater	55
45.	Effect of Heater Position on Heat-transfer Coefficients in Fluidized Beds with 138- μm -diam Glass Beads and 0.5-in.-long Heater	55
46.	Effect of Heater Position on Heat-transfer Coefficients in Pulsed Beds with 580- μm -diam Glass Beads and 0.5-in.-long Heater	56
47.	Effect of Heater Position on Heat-transfer Coefficients in Pulsed Beds with 138- μm -diam Glass Beads and 0.5-in.-long Heater	56
48.	Effect of Static-bed Height on Heat-transfer Coefficients in Fluidized Beds (Particles: 138- μm glass beads; heater length: 0.5 in.; heater position: 3 in.)	57
49.	Effect of Static-bed Height on Heat-transfer Coefficients in Pulsed Beds, with 0.5-sec On-period and 0.5-sec Off-period . .	57
50.	Effect of Static-bed Height on Heat-transfer Coefficients in Pulsed Beds, with 0.2-sec On-period and 0.6-sec Off-period . .	57
51.	Effect of Static-bed Height on Heat-transfer Coefficients in Pulsed Beds, with 0.125- and 0.25-sec On-periods and 0.375- and 0.25-sec Off-periods	57
52.	Effect of Heater Length on Heat-transfer Coefficients for 580- μm Glass Beads	58
53.	Effect of Heater Length on Heat-transfer Coefficients for 138- μm Glass Beads	58

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
54.	Heat-transfer Coefficients for an Aluminum-Air System (Average diameter of particle: 291 μm)	59
55.	Heat-transfer Coefficients for a Copper-Air System (Average diameter of particle: 313 μm)	59
56.	Effect of Solid Thermal Properties on Heat-transfer Coefficients	60
57.	Bed Stroke vs Pulsed-gas Velocity for Various Gases	60
58.	Pulsed-bed Movement with Carbon Dioxide and Air	61
59.	Heat-transfer Coefficients for Fluidized and Pulsed Beds with Air	61
60.	Heat-transfer Coefficients for Fluidized and Pulsed Beds with Carbon Dioxide	61
61.	Heat-transfer Coefficients for Fluidized and Pulsed Beds with Helium	61
62.	Instantaneous Particle-residence Time in a Pulsed Bed	63
63.	Data Comparison with Predictions for 580- μm Glass Beads with 0.125-sec On-period and 0.375-sec Off-period	65
64.	Data Comparison with Predictions for 580- μm Glass Beads with 0.25-sec On-period and 0.25-sec Off-period	65
65.	Data Comparison with Predictions for 580- μm Glass Beads with 0.25-sec On-period and 0.5-sec Off-period	66
66.	Data Comparison with Predictions for 138- μm Glass Beads with 0.2-sec On-period and 0.6-sec Off-period	66
67.	Data Comparison with Predictions for 138- μm Glass Beads with 0.2-sec On-period and 0.4-sec Off-period	66
68.	Pulsed-bed Operation in Two Parallel Columns	68

LIST OF TABLES*

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Properties of Materials Used	26
II.	Combinations of Experimental Variables	32
III.	Minimum Fluidization and Bubbling Velocities	33
IV.	Comparison of Model with Data	50
V.	Predicted Heat-transfer Coefficients	51
VI.	Maximum Heat-transfer Coefficients and Nusselt Numbers for Various Gases	61
VII.	Average Residence Time of Particles for One Cycle of Pulsation	63

*Tables contained in the appendixes are listed at the front of each appendix.

NOMENCLATURE

A	= cross-sectional area of a column	T_b	= bed temperature
A_h	= heater surface area	T_{pN}	= temperature of Nth particle
a	= lag factor	t	= time
B	= constant	t_{on}	= on-period
b	= fraction of particles that do not contact a heater more than once in consecutive pulses	t_{off}	= off-period
c	= constant	t_p	= period of one cycle of pulsation
c_p	= heat capacity of liquid	t_r	= period for resting particle
C_p	= solid specific heat	$ \bar{U} $	= absolute average velocity of particle
D_b	= diameter of largest bubble in system	$U_i(t)$	= instantaneous velocity of ith particle
D_p	= average particle diameter	$U(t)$	= instantaneous average particle velocity
D_{ps}	= average particle diameter on the screen	u_b	= velocity of rising gas bubbles in a freely bubbling fluidized bed
D_t	= heat-transfer-tube diameter	u_{b0}	= velocity of rising gas bubbles in an incipiently fluidized bed
f_N	= fraction of period for particle input	u_{db}	= velocity of descending bed surface
f_{ps}	= film speed	U_p	= velocity of individual particle
g	= gravitational constant	v	= pulsed-gas velocity (superficial gas velocity based on on-period only)
H_{mf}	= minimum fluidized-bed height	v_0	= integral gas velocity (superficial gas velocity based on an entire pulse period)
h	= heat-transfer coefficient	v_{mb}	= minimum bubbling velocity
$h_c(\bar{\tau})$	= calculated heat-transfer coefficient corresponding to the residence time, $\bar{\tau}$	v_{mf}	= minimum fluidization velocity
h_0	= experimental constant	v_{rms}	= root-mean-square liquid velocity
K	= constant	W	= charged weight in a bed
k	= thermal conductivity of liquid	x	= location of a particle at any time
$k_{1,2,3}$	= fraction of time period	x_1	= location of a particle at time t
k_0	= average mass-transfer coefficient for steady flow	x_2	= $\mathcal{L} - x_1$
$\bar{k}_p$	= average mass-transfer coefficient for pulsed flow	α_p	= pulse Reynolds number (packed bed)
k_{em}	= effective thermal conductivity	β	= fraction of particles that move away from the surface
$k_{em,\eta}$	= effective thermal conductivity when particles are separated by ηD_p	ϵ	= void fraction
k_g	= gas thermal conductivity	ϵ_0	= void fraction of minimum fluidized bed
k_s	= solid thermal conductivity	ρ	= density of liquid
$\mathcal{L}$	= heater length	ρ_p	= solid density
$\mathcal{L}_i$	= location of ith particle at nth frame on the screen	λ	= mean travel distance of particle
L_1	= function of x_1 and t	η	= gas-gap factor
L_2	= function of x_2 and t	μ	= viscosity
m	= constant	$\bar{\tau}$	= average particle residence time
N	= particle flux	τ_0	= average particle residence time for one cycle of pulsation
Nu	= Nusselt number	$\tau(t)$	= instantaneous mean residence time
p	= constant	$\tau_1(t)$	= average time that particles stay at the heater surface after a given time t
ΔP_{max}	= maximum pressure drop	$\tau_2(t)$	= average time that particles have remained on the surface until time t
P	= persistence factor	τ'_{11}	= time when a particle located at a distance x_1 from bottom of heater leaves the surface
$\dot{q}$	= heat flow in annular differential element	τ'_{22}	= time when a particle located at a distance x_2 from top of heater arrives at that location
$\bar{q}$	= heat flow between two particles	τ_r	= particle residence time for resting
Q	= heat input	τ_{up}	= particle residence time during upward motion
r	= radial position	τ_{down}	= particle residence time during downward motion
$S_p(t)$	= average particle travel distance	θ	= time
S_b	= bed stroke		
T_s	= surface temperature		

PULSED-BED APPROACH TO FLUIDIZATION

by

Masaru Kobayashi

ABSTRACT

An important objective of this investigation is to explore pulsed-bed characteristics that result from controlled, intermittent gas flow. Four sizes of glass beads ranging from 73 to 580 μm in average diameter, were tested in 4-in.-OD, 1.25-in.-ID annular columns to find the unique characteristics of pulsed beds, as follows:

1. The bed expansion ratios increase with gas velocity and decrease with pulse frequency and fraction of on-period.
2. Good particle motion exists below the minimum fluidizing velocity.
3. The stroke of the bed can be predicted from on-period, gas velocity, and minimum bubbling velocity.

The characteristics of heat transfer from an internal heater to a pulsed bed have been studied regarding the effects of pulsing conditions, particle and gas properties, heater position, heater length, and static-bed height. Pulsed-bed operation has remarkable advantages in a heat-transfer process with large sizes and heavier particles, short heaters, and heaters located in the upper part of a bed.

With the proposed heat-transfer mechanism model and the predicted bed stroke, the heat-transfer coefficients in a pulsed bed can be estimated.

I. SUMMARY

The pulsed-bed approach to fluidization, which results from controlled, intermittent gas flow, appears to have certain advantages in gas-solid contacting. The application of pulsed-bed operation has been increasing; however, pulsed-bed characteristics such as bed behavior and heat- and mass-transfer characteristics have not as yet been elucidated. An important objective of this investigation is to explore pulsed-bed characteristics.

Four sizes of glass beads, ranging from 73 to 580 μm in average diameter, were tested in 4-in.-OD and 1.25-in.-ID annular columns to measure the bed expansion and pressure drops. The unique characteristics of pulsed beds have been found to be:

1. Pressure-drop patterns are reproducible for each pulse cycle.
2. Maximum pressure drop increases linearly with pulsed-gas velocity.
3. The bed-expansion ratios increase with
 - a. Increasing gas velocity
 - b. Decreasing pulse frequency
 - c. Decreasing fraction of on-period.
4. Larger or heavier particles have more regular dependence on pulsing conditions.
5. Good particle motion exists below the minimum fluidizing velocity.
6. There exists an upper limit of on-period, which can be predicted from the rising velocity of bubbles, and a lower limit of off-period, which can be predicted from the velocity of descending beds, for a fully controlled pulsed-bed behavior. The stroke of the bed can also be predicted from on-period, gas velocity, and minimum bubbling velocity.

The characteristics of heat transfer from an internal heater to a pulsed bed have been studied regarding the effects of pulsing conditions (gas velocity and on- and off-period), particle properties (four sizes of glass beads, aluminum shot, and copper shot were used), gas properties, heater position, heater length, and static-bed height. Pulsed-bed operation has remarkable advantages in a heat-transfer process with large sizes of particles, heavier particles, short heaters, and heaters located in the upper part of a bed.

A model for the heat-transfer mechanism in gas-particles system has been proposed. The basic assumption of this model is that heat flows perpendicularly through gas and particles that are separated with gas gap ηD_p . Heat-transfer coefficients calculated from the particle residence time and particle flux that were measured from high-speed motion pictures were compared with experimental data. The agreement was satisfactory.

With heat-transfer mechanism model and the predicted bed stroke, the heat-transfer coefficients in a pulsed bed can be estimated.

II. INTRODUCTION (STATEMENT OF THE PROBLEM)

A bed of solid particles can be maintained in a fluidized state if the gas flowing upward through the bed is kept within the proper velocity range. Similarly, a pulsed, intermittently fluidized bed results from controlling the gas so that it flows intermittently. The pulsed-bed approach to fluidization appears to offer certain advantages in gas-solid contacting.

In pulsed-bed operations, the bed expands during a gas pulse, then contracts during the interval when the gas flow is shut off. During each pulsing cycle, the solids may exist in four distinct states: With rapid transition, they (1) undergo pneumatic transport, (2) behave as a fluidized bed, (3) undergo hindered settling, and (4) return to the static-bed condition. Possible advantages of pulsed-bed operation are (1) capability of using wider ranges of particle sizes, (2) better solids-gas contacting with large as well as small particles and improved reactant utilization, (3) improved heat- and mass-transfer rates between gas and solid particles, as well as between a boundary surface and a bed, and (4) greater gas flowrates, especially for small sizes of particles without elutriation of particles from the bed.

In the literature to date on the use of pulsing-gas streams for gas-solid contact, no data were available on pressure drop or bed expansion of pulsed beds in cylindrical columns. Further, in the previous work, the on-period of the pulse cycle was arbitrarily selected without systematic experimental investigation of the effect of the ratio of on-period to off-period on the behavior of pulsed beds. Although primary attention in this investigation is to the exploration of heat-transfer characteristics in a pulsed bed with the ultimate objective of presenting a mechanism of heat-transfer applicable generally to fluidized and pulsed beds, a better understanding of the characteristic behavior of a pulsed bed must be developed. For this purpose, the effects on the pressure-drop pattern, maximum pressure drop, bed expansion, and bed movement of various pulsing conditions such as frequency of pulsation, ratio of on-period to off-period, and gas flowrate were first studied. —

The heat transfer between a boundary surface and a fluidized bed is understood to depend on the population and the residence time of solid particles at that surface. Several models have been proposed for the heat-transfer mechanism; however, each of these models has some drawbacks. This report proposes and discusses a relatively simple mathematical heat-transfer model, based as much as possible on the actual physical phenomena of fluidized or pulsed beds. Calculations based on the model were carried out by means of a digital computer.

Pulsed-bed operation may provide shorter residence times of particles and less gas void (greater solid population) at the boundary surface

than do fluidized beds at the same gas throughputs. It follows, therefore, that in certain regimes of bed operation the pulsed bed may be expected to improve heat transfer over fluidized beds. To date, only limited data on heat-transfer rates in pulsed beds have been made available. One objective of this work is to explore heat-transfer characteristics in a pulsed bed, giving attention to the effect of (1) particle size, (2) pulsing conditions (on- and off-period), (3) heater position in beds, (4) static-bed height, and (5) heater length. The heat-transfer characteristics of a pulsed bed are compared with those of a fluidized bed. Means are also sought for estimating the heat-transfer coefficients in a pulsed bed from the bed movement by using the model that is proposed.

III. LITERATURE SURVEY

A. Pulsed-bed Studies

There have been several studies describing mixing of solids, heat transfer, drying, chemical reactions, and other observations in gas-solid pulsed-bed systems. Each of these studies emphasized the advantage of pulsed-bed operation.

Massimilla, Volpicelli, and Raso¹ studied pulsed beds in a rectangular column with 7.9- by 0.6-in. inside dimensions and in a cylindrical column with a 7.9-in. inside diameter. Data obtained with the rectangular column were reported on pressure drops and bed expansions for various frequencies (0-6 Hz with 50% on-period) and gas flowrates with beds of glass beads (600-3100 μ m in diameter). Pressure drops were higher for pulsed beds than for fluidized beds at equivalent gas throughputs. The authors of Ref. 1 pointed out that the data obtained in experiments with the rectangular column have been variously influenced by the frictional forces between the solid and the container and by the wall effects on bed-porosity and gas-velocity profiles. Further, the authors suggested that the heat transfer from a surface to the bed in a rectangular column could be expected to be less for the pulsed mode than for the normal mode of fluidization. However, they concluded that the uniformity of solid-gas contact peculiar to fixed-bed operation and the solid motion peculiar to fluidized-bed operation are, to some extent, combined in a pulsed-bed operation. Pulsation of the fluidizing gas attenuates channeling and bubbling of gas in beds of particles, although quite active circulation of solids is maintained.

Berg and Miniscalco² described a commercial air-pulsed mixer of 5000-lb capacity that blends six ingredients (limestone, mica, talc, asbestos, clay, and casein or PVA binder) solely by intermittent blasts of air at the bottom of the bed. The mixer is 14.5 ft high, and its cylindrical section is 6 ft in diameter. The bulk densities of the materials range from 11 to 60 lb/ft³, and the particle sizes range from 10 to 600 μ m. The air-pulsed mixer gave better mixing than three mechanical blenders that it replaced, with resultant improvement in product uniformity by 300%, increase in capacity by 100%, and reduction in operating labor costs by 20% per lb of material produced.

With pulse frequencies of 0.5, 1.0, 1.5, and 2.0 Hz, and with a 50% on-period, Bokun and Zabrodskii³ investigated heat transfer between a pulsing bed of fine dry sand and a heater immersed in it. The pulsed-bed column diameter was 2.2 in., and the concentric-heater diameter was 0.2 in. The mean diameters of the dry quartz sand were 180, 257, 357, 515, and 815 μ m. The experimental data showed that heat-transfer coefficients increased as the gas velocity was increased. In a range immediately above the minimum fluidization velocity, the heat-transfer coefficients were

higher by several factors for pulsed beds than for fluidized beds at the same integral gas throughput. The maximum heat-transfer coefficient for this pulsed-bed system, about $60 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$, was obtained at integral gas velocities smaller by 30-40% for pulsed beds than for conventional fluidized beds. The best heat transfer was obtained in both cases by the contact of the heating surface with dense beds of particles that interchanged rapidly near the surface.

Drying of moist tetracycline, which could not be carried out in an ordinary fluidized bed, was carried out satisfactorily in a pulsed bed by Zabrodskii and Bokun.⁴ The pulsed-bed column was 2.2 in. in diameter; the column, the auxiliaries, and the operating conditions were similar to those used in the previous investigation. When drying was attempted with a steady flow of air upward through a bed of moist tetracycline, channeling occurred, resulting in irregular drying and poor utilization of the drying gas. However, with the pulsing flow of gas, channels did not form, and the bed moved vigorously, resulting in better heat and mass transfer and good utilization of the drying gas. The heat-transfer coefficients from the internal-heater surface to the moist tetracycline bed increased with increasing gas throughput, and the other trends in the data were similar to those observed in the previous investigation. The improvement in heat- and mass-transfer coefficients between air and moist tetracycline was evidenced in data on reduction in the moisture content of the tetracycline during drying by both methods; e.g., with a steady gas flow, the moisture content decreased from 40 to 33 wt % in 1 hr, whereas with a pulsed-gas flow the moisture content decreased from 40 to 10 wt % in 1 hr.

Belik⁵ reviewed three years of experience in operating commercial pulsed-bed dryers. He outlined various operating procedures for drying various types of materials. Organic granular products with moisture contents up to 25% were dried in batches up to 1000 kg. The particle sizes of the organic products ranged from 10 to 3000 μm , the particles were of various shapes, and the bulk densities ranged from 0.5 to 0.8 g/ml. The on-period of the pulse cycle was ~33%, and the frequencies of pulses ranged from 0.4 to 1.2 Hz, depending on the bed depth. Gas was fed in turn through each of the five ports located on the circumference of the gas distributor. A gas pulse was introduced through one port, and the subsequent pulse was introduced through the port diagonally across the original port. The gas pulse was allowed to expand after introduction into the bed. This pulsation procedure eliminated channel formation, even in deep beds. The drying time was about one-third to one-sixth of that in a conventional vacuum oven, the energy consumption was about one-half of that in the vacuum dryer, and the drying was more uniform than in the conventional dryer.

Levey *et al.*^{6,7} used pulsed beds for (1) reduction of U_3O_8 to UO_2 and then hydrofluorination of the resulting UO_2 to UF_4 , (2) reduction and hydrofluorination of ammonium diuranate filter cake, (3) reduction and

hydrofluorination of ammonium diuranate centrifuge cake, and (4) conversion of massive uranium metal chips to uranium hydride, and then thermal decomposition of the hydride to uranium powder. Conducting these reactions in pulsed-bed reactors resulted in products with the desired physical and chemical properties, whereas conducting these in fluid-bed reactors, fixed-bed reactors, or rotary calciners did not yield satisfactory products.

Hydrogen reduction of U_3O_8 particles with diameters less than $100\ \mu\text{m}$ was conducted at $1000\text{--}1100^\circ\text{F}$ for 1.5 hr with a pulse frequency of 0.73 Hz and an integral gas velocity of $\sim 2.0\ \text{ft/sec}$. The hydrofluorination was conducted at $500\text{--}1000^\circ\text{F}$ for 6.5 hr with a pulse frequency of 0.6 Hz and an integral gas velocity of $\sim 1.5\ \text{ft/sec}$. The total processing time was 8 hr. When the same U_3O_8 was processed with a steady flow of gas, the maximum gas velocity attainable without packing the solid against the top of the reactor was $0.1\ \text{ft/sec}$, and the total time for reduction and hydrofluorination was 24 hr. These data reported by Levey *et al.* illustrate that with the use of pulsed beds a great increase in integral gas velocity through the bed is possible and the time required to complete a reaction is markedly reduced.

Ammonium diuranate filter cake having a particle size distribution of from approximately $1\text{--}5000\ \mu\text{m}$ was successfully processed in pulsed beds. Conventional steady-gas-flow fluidization techniques were not applicable to the processing of this filter cake.

In pulsed beds, massive uranium machine chips were reacted with hydrogen at 450°F until the conversion to uranium hydride was completed,⁷ and then the hydride was thermally decomposed at 1000°F to uranium powder. The particle-size distribution of the product was such that 95% of the product was less than $5\ \mu\text{m}$ and 90% less than $1\ \mu\text{m}$. Because of caking and sintering, conventional fluidized beds or rotary calciners were impractical for producing the uranium powder.

In the literature to date on the use of pulsing-gas streams for gas-solid contact, no data of importance in process applications were reported on pressure drops, bed expansions, and mixing characteristics of pulsed beds in cylindrical columns. Further, in all the previous work, the on-period of the pulse cycle was arbitrarily selected without systematic experimental investigation of the effect of the ratio of on-period to off-period on the bed behavior.

Several authors have studied mass and heat transfer in pulsed beds of liquid-solid systems. Krasuk and Smith⁸ studied the effect of pulsating the water flow to the packed bed by means of a piston pump on mass-transfer rates from the walls and from the particles. Their experimental parameter was the rate of dissolution of β -naphthol from the wall and from the particles within the bed. They correlated the mass-transfer coefficients in pulsed flow

in a packed bed with a pulse Reynolds number and a dimensionless pulsed-gas velocity by means of the equation

$$\frac{\bar{k}_p - k_0}{k_0} = 0.75(v\alpha_p)^{0.30}, \quad (1)$$

where

$\bar{k}_p$ = average mass-transfer coefficient for pulsed flow,

k_0 = average mass-transfer coefficient for steady flow,

v = pulsed-gas velocity,

and

α_p = pulse Reynolds number (packed bed).

They concluded that the improvement in $\bar{k}_p$ increased with increasing frequency and decreased with increasing average flowrates. In their work, no particle movement was involved.

Hogg and Grimmett⁹ studied effects of pulsation on heat transfer in a liquid-fluidized bed. They measured heat-transfer rates from heat-transfer tubes immersed in water-glass-bead fluidized beds pulsated by a piston pump. They indicated that heat-transfer rates from a liquid flowing normal to a cylinder could be increased as much as two and a half times when the cylinder is surrounded by a bed of fluidized particles, and an additional four times when the fluidized system is pulsed. The heat-transfer rates were determined to be a strong function of pulse frequency and displacement amplitude, and the greatest improvement was realized at the highest pulse stroke, which was defined as the product of the pulse frequency and the displacement amplitude. They correlated the heat-transfer coefficients with the root mean square of the fluid velocity as

$$\frac{hD_t}{k} = 0.153 \frac{D_t V_{rms} \rho}{\mu} \left(\frac{D_t}{D_p} \right)^{0.32} \left(\frac{c_p \mu}{k} \right)^{0.33}, \quad (2)$$

where

h = heat-transfer coefficient,

k = thermal conductivity of liquid,

D_t = heat-transfer-tube diameter

D_p = particle diameter,

V_{rms} = root-mean-square liquid velocity,

ρ = density of liquid,

μ = viscosity,

and

c_p = heat capacity of liquid.

B. Heat-transfer Mechanism in Fluidized Beds

A number of models describing the heat-transfer mechanism between a boundary surface and a fluidized bed have appeared in the literature. Several interesting models are described here in the chronological order of publication.

Mickley and Trilling¹⁰ and Levenspiel and Walton¹¹ stated that the primary resistance to heat transfer is located in a thin fluid film near the heater wall. Heat flows through the fluid film by conduction as well as by convection. The thickness of the film is probably reduced by the eddies created by the movement of particles at the wall, with a resultant improvement in the heat-transfer rate.

Mickley and Fairbanks¹² described another heat-transfer mechanism as follows: Small groups of particles referred to as "packets" are imagined to move as individual units through the bed as the dense phase is stirred by bubbles. A packet has the properties of the bed at minimum fluidization. This packet receives heat by unsteady-state diffusion of heat for a time after arriving at the heated surface, and then returns to the bulk of the bed. The heat-transfer coefficient is proportional to the square root of the packet thermal conductivity, specific heat, density, and a stirring factor that accounts for the residence time of the packet.

Jacob and Osberg¹³ proposed a semiempirical heat-transfer mechanism assuming (1) heat transfer occurs only by conduction through a gas film, and solid-solid heat exchange is negligible; (2) thermal contact between one particle and the heater surface is established during a certain time, τ , which is the average value and applies to all particles of a particular fluidized bed; (3) heat transfer by forced convection to the gas phase is negligible; and (4) there is no temperature gradient within the particles. They derived the equation for heat-transfer coefficients as

$$h = h_0(1 - \epsilon)(1 - e^{-p k g}), \quad (3)$$

where h_0 and p are experimental constants.

Ernst¹⁴ proposed a heat-transfer mechanism combining steady-state conduction through a gas layer at the heater surface and unsteady-state transfer into a packet that has the properties of the bulk bed. At high values

of contact time, heat transfer corresponds to unsteady-state transfer, and as contact time becomes smaller, steady-state conduction through a gas layer limits the heat-transfer rate. At very high gas rates, the heat-transfer characteristics of more rapid particle motion are offset by a corresponding increase in voids.

Zabrodskii^{15,16} stated that the main resistance to heat transfer exists in a very thin fluid interlayer between the wall and the first row of particles. The particles in this row are assumed to remain nearly as cool as the bulk of the bed, because of the short residence time. The temperature gradient in the particle is assumed negligible compared with the temperature difference between the wall and the particle surface. Also, no heat penetration is assumed beyond the first layer of particles.

Mickley, Fairbanks, and Hawthorn¹⁷ studied their model¹⁰ further with experiments using a small-sized and very small-heat-capacity heater placed in various vertical positions in the bed. From the fluctuations of local heat-transfer coefficients observed, they hypothesized that periods of zero coefficient occur when gas bubbles pass the heater surface, and that ensuing jumps in coefficient are due to the sudden contacting of packets of solid with the surface.

Brusenback,¹⁸ using a model consisting of a string of four beads next to the heater surface, assumed the following mechanism: All heat transferred from the heater is removed by the beads and none by the gas. The beads approach the heater surface at the bulk temperature of the bed, move across the surface at some velocity, and always remain in contact with the surface until they depart from the heater surface. Heat is transferred to an individual bead only by conduction through the gas space and not by convection. The gas layer active in heat transfer is all resistance and no capacitance. The bead is all capacitance and no resistance. The spherical-bead surface is approximated by a hypothetical conical shape, in which heat transfer is only in the angular direction and not in the radial direction. This model has been approximated by an analog computer using the particle velocity and population at the heater surface that was determined from a motion picture taken at a simulated heater surface.

Botterill and Williams¹⁹ considered the heat-transfer mechanism in a fluidized bed as the transient heating of a single sphere at a heater surface for two cases: (1) direct contact of the solid and the surface, and (2) the existence of a gas gap between the particle and the heater surface. They calculated the variation in the heat flux with the residence time of the sphere at the heater surface by numerical solution of the energy equation for the gas-sphere system. The average heat-transfer coefficients were compared with experimental data obtained in a stirred fluidized bed. The particle residence time was determined from the revolution of the

stirring blade. They concluded that fluidized particles are closely packed at the walls of the bed and very close to, if not in contact with, the heat-transfer surface.

Baskakov²⁰ proposed a similar model to Mickley and Fairbanks' model,¹² but added a contact resistance to heat transfer between the heater surface and the packet based on the change in the effective thermal conductivity and heat capacitance of the bed near the wall in a zone having a thickness of about one particle diameter. This additional resistance to heat transfer was assumed to be independent of time and was determined from a steady-state process. Thus, the maximum value of heat transfer is limited by this contact resistance.

Ziegler, Koppel, and Brazelton²¹ proposed a model considering a single particle that absorbs heat by convection. They regarded this mechanism as the transient heating of a cold sphere, with an initial temperature the same as the bulk temperature of the bed, surrounded by a stagnant gas at the heater surface temperature. They used a gamma function for a residence-time distribution to obtain a time-averaged heat-transfer coefficient. They also mentioned that, in accordance with this model, the maximum Nusselt number in fluidized beds is 7.2.

Wasmund and Smith²² proposed a model similar to that of Ziegler et al.²¹ Heat is transferred by convection as particles pass through the thermal region near the heater surface where the temperature gradient exists. A particle enters the thermal region with a certain radial velocity and at the temperature of the bulk of the bed. The particle proceeds through the thermal region, gaining heat from the surroundings, arrives at the wall, and then returns through the thermal region to the core of the bed with a higher temperature than that of the bulk of the bed. Wasmund and Smith estimated the thickness of the thermal region and the average particle flux to carry out the calculation of the model.

Botterill et al.²³ extended the work of Botterill and Williams¹⁹ and estimated the heat-transfer coefficients for solids of different thermal properties. They stated that the single-particle model was not adequate for long particle-residence time and showed the validity for short residence time.

Botterill et al.^{24,25} improved this model^{19,23} to a two-particle model and presented the data for a stirred fluidized bed and a moving bed. They postulated that the theoretical prediction for the model of a particle in contact with the heater surface provides higher values than the experimental values. Discrepancy is most marked for copper shot. Therefore, they proposed a gas gap between the particles and the heater surface, which becomes the controlling resistance for short residence time and for a material of good thermal diffusivity. This gas gap was chosen as 10% of the particle diameter.

Couderc, Angelino, and Enjalbert^{26,27} reported a model similar to that of Botterill et al. and emphasized the distance separating the surface and the particles.

Patel²⁸ proposed two models, one of which was essentially the same as Baskakov's contact-resistance model.²⁰ The other model assumes that a particle at the temperature of the bulk of the bed arrives at the heating surface, and while the particle is at the surface it receives heat by convection from the fluid adjacent to the surface. This fluid is assumed to be at the heater-surface temperature and to be stagnant. The Nusselt number between the gas and the particle is assumed to be 2. Also, the particle at the surface loses heat by conduction to a packet of particles of a certain thickness situated next to the surface particle. Patel measured the number of tracer particles at the heater surface as a function of time to determine the average particle-residence time by a statistical method.^{29,30} His first model, the one similar to Baskakov's, agreed quite well with his experimental data with glass beads; however, for copper shot, his second model was satisfactory.

The models for the heat-transfer mechanism proposed in the literature have been presented above without my opinions and criticism, which are presented in Section V.

IV. EXPERIMENTAL APPARATUS, PROCEDURE, AND ANALYSIS

A. Apparatus

Figure 1 is the flowsheet of the apparatus for the experiment. Feed gas, either from compressed-gas cylinders or from the house air supply,

308-1953

Fig. 1. Flowsheet of Experimental Apparatus

is passed through two gas pressure regulators (1, 2); one regulator limits the maximum pressure to 20 psi for safety, and the other controls the gas flowrate. Part of the gas stream is passed through a rotameter (4) and then through a humidifier (5). The humidified gas is combined with dry gas and fed to a gas-mixing chamber (6). The humidifier is a 3-in.-ID, 4-ft-tall Lucite tower filled with ceramic Raschig rings and water. The humidified gas is passed through an integrating gas meter (7) to a surge tank (capacity of 7.35 ft³). The humidity of the gas in the surge tank (8) is measured by withdrawing a small sample and using a dew cup meter (10). The humidity is maintained at 4-5 g of water per 1000 g of dry gas to eliminate the deleterious effect of static charges and adhesive forces. Intermittent gas flow to the pulsed-bed column is accomplished with a solenoid valve (3/8-in. orifice, 3/8-in. pipe size) located in the line between the surge tank and the column. The solenoid valve is controlled by a repeat-cycle timer (16).

The outer column (13) is a 4-in.-ID, 4-ft-long Pyrex glass pipe, and the inner column (not shown in the figure) is a 1 $\frac{1}{4}$ -in. -OD Pyrex tube. Both are coated (by Corning Glass Works) with a mixture of Sb₂O₃ and SnO₂ to reduce the deleterious effects of static charges. This type of annular column is selected to facilitate the observation of the bed as well as measurement of heat-transfer coefficients from an internal surface to the pulsed bed. In the heat-transfer studies, the outer pipe is replaced with a 4-in.-ID, and 4-ft-tall brass tube with a 4.65-in.-OD jacket (see Fig. 2). The thickness of the tube wall is 0.05 in.; that of the jacket wall is 0.075 in. Cooling water is passed through the jacket, which is insulated with glass wool. The inlet and outlet temperatures of the cooling water are measured to maintain the same experimental conditions for each run. The inner tube is replaced with a heater, as shown in Fig. 2. The heater is held in position by a Micarta

tube (heat-resistance material by Westinghouse Electric Co.). A Teflon ring is used as insulation between the heater and the Micarta tube as well as a holder for the heater (as shown in Fig. 3). The heaters are cartridge type (made by Watlow Electric Manufacturing Co.), with a maximum heat flux of 127 W/in.^2 . The heat from the element is conducted through a copper ring to the surface, where it is transferred to the pulsed bed. The outside diameter of the heat-transfer surface is $1\frac{1}{4}$ in. Lengths of $1/2$, 2, and 4 in. for the heat-transfer surface are obtained with various heater-element and copper-ring combinations. A variac controls the heat input by regulating the voltage to the heater.

308-1951

Fig. 2. Pulsed-bed Column

308-1952

Fig. 3. Internal Heater

The bottom section of the column is an inverted truncated brass cone (4-in. base and 2-in. apex) with a concentric $1\frac{1}{4}$ -in.-OD, 1-in.-ID inner tube. The gas inlet has a $7/16$ -in. ID and is connected to the apex. A sintered stainless steel plate ($1/8$ in. thick) is used as the gas distributor (12).

The top section of the column is a 4-in.-ID, 3-in.-high inverted cup, with a concentric coupling to hold a $1\frac{1}{4}$ -in.-OD tube (either a heater holder for heat-transfer measurements or a glass tube for visual observations). Also, two thermocouple wells and a pressure tap are provided.

The pressure taps of the column are connected to unbonded strain-gauge differential-pressure transducers (14, Fig. 1), made by Statham Instruments, Inc. The pressures are recorded on a Visicorder (15), made by Honeywell, Inc.

An iron-constantan thermocouple with a 0.02-in.-OD sheath is imbedded in the heat-transfer surface to measure the surface temperature. The temperature of the heat-transfer surface is recorded on a single-pen chart recorder. An iron-constantan thermocouple with 0.04-in.-OD stainless steel sheath and an exposed junction is immersed in the pulsed bed to measure the bed temperature. The thermocouple is held in position by a $1/8$ -in.-OD protective tube, and the location of the thermocouple junction can be adjusted to the desired height. The pulsed-bed temperature is recorded on a single-pen fast-response recorder (made by Honeywell, Inc.). The gas stream is completely shut off to check if the immersed thermocouple is picking up correct bed temperature after steady state is attained. All the remaining temperatures of the pulsed-bed column are measured by iron-constantan thermocouples and are recorded on a multipoint temperature recorder.

An internal viewer developed by Brusenback¹⁸ was used to observe and photograph the behavior of particles at the surface of the inner Pyrex column, which is similar to the heat-transfer surface described earlier. The principle of the viewer is mirror reflection. The light from a source placed on the top of the column was reflected on the surface of observation by one mirror, the view of the surface was reflected by another mirror to the bottom of the column, and the view was observed or photographed. A Milliken Model DBM5-2 camera, which gives the film speed in the range of 2 to 500 frames per second (fps), was used for photographing.

B. Material Used

Table I lists the physical and thermal properties of the particles and the gas used in this experiment. For the photographic studies, 580- μm red and white glass beads were used. (The beads were purchased from Engineering Abrasives.) For a view of bead rotation at the wall, colored beads were covered with a white coating, and then the coating was removed from one side of the beads. For this, tissue paper was soaked in a solution of india ink-50% acetone. The wet tissue paper was placed on a flat surface, and the white-coated beads were placed on it in a single layer. The acetone-soluble coating was thus removed from the side of the beads touching the paper.

TABLE I. Properties of Materials Used^a

	Average Diameter, μm	Density, lb/ft^3	Specific Heat, $\text{Btu}/(\text{lb})(^\circ\text{F})$	Thermal Conductivity, $\text{Btu}/(\text{ft})(\text{hr})(^\circ\text{F})$
No. 1 glass beads	580	154	0.17	0.5
No. 2 glass beads	301	154	0.17	0.5
No. 3 glass beads	138	154	0.17	0.5
No. 4 glass beads	73	154	0.17	0.5
Aluminum shot	292	169	0.224	117.5
Copper shot	313	557	0.10	222

	Density, lb/ft^3	Specific Heat, $\text{Btu}/(\text{lb})(^\circ\text{F})$	Thermal Conductivity, $\text{Btu}/(\text{hr})(\text{ft})(^\circ\text{F})$	Kinematic Viscosity, ft^2/hr
Air	0.0709	0.241	0.016	0.648
Carbon dioxide	0.11	0.203	0.010	0.352
Helium	0.0101	1.24	0.088	7.39

^aProperties are at 100°F.

C. Procedure and Analysis

1. Definition of Integral Gas Velocity and Pulsed-gas Velocity

The gas stream is intermittently fed to the pulsed column in rectangular pulsations. The gas feed period, during which the valve is open, is referred to as the on-period, t_{on} ; the period during which the gas stream is shut off is referred to as the off-period, t_{off} . The gas velocity averaged over the complete pulse period is referred to as the integral gas velocity, v_0 ; the gas velocity based only on the on-period is defined as the pulsed-gas velocity, v . These definitions are illustrated in Fig. 4.

Fig. 4
Illustration of Pulsed gas Velocity
and Integral Gas Velocity

For reduced gas velocity, two standard velocities are used. One is the minimum fluidization velocity, v_{mf} , determined from the pressure-drop patterns; the other is the minimum bubbling velocity, v_{mb} ($>v_{mf}$), which is the velocity at which bubbling starts in the bed. Minimum fluidization velocity is used mainly for pressure drops and bed expansions. Minimum bubbling velocity is used for heat transfer.

2. Pressure Drops

Pressure was changed to electrical excitation by a differential pressure transducer and was recorded on a Visicorder. On the Visicorder chart, 1 psi corresponds to 4.4 in. Chart speed was set at 2 in./sec. The maximum pressure drop ΔP_{max} was read from this chart and was divided by a theoretical fluidization pressure drop W/A , as $A\Delta P_{max}/W$, where A is the cross-sectional area of the column and W is the weight of particles charged.

3. Bed Expansion

The maximum bed expansion was measured mostly by visual observation with the scale on the outer column. Motion pictures were taken to obtain the bed surface movement and the time-history curve. TRI-X reversal film (ASA 200) and Ektachrome EF (ASA 125) were used. Film speed was 100 frames/sec. The outer column was illuminated by two 500-W floodlights and an aperture setting of f11. The pictures were analyzed using a Vanguard Motion Analyzer. The scale on the outer column was used directly for analysis.

4. Particle Velocity, Travel Distance, and Residence Time in Pulsed Beds

Motion pictures at a film speed of 200 fps were taken to obtain the particle-velocity profile at the internal surface using Brusenback's¹⁸ internal viewer. A 600-W Sun Gun was used as a light source. The film used was Ektachrome EF, for which the recommended ASA speed is 125. The film was used at an ASA speed of 500, and special processing procedures were used. A 152-mm telephoto lens with a 4-in. extension tube was adopted. The iris on the lens was set at f4.5, which gives an actual aperture of f7.5, because of the extension tube. The 60-Hz timing light was recorded on the edge of the film.

As tracer particles, white-coated glass beads were mixed with red glass beads. Glass beads with a 580- μm average diameter (D_p) were used. The number of tracer particles on a single frame was 30-60.

The motion pictures were analyzed frame by frame with a Vanguard Motion Picture Analyzer to obtain:

- The instantaneous average particle velocity, $U(t)$.
- The average travel distance of particles, $S_p(t)$.
- The instantaneous mean residence time $\tau(t)$.
- The average residence time of particles, $\bar{\tau}$.

The magnification was determined from the average diameter of particles on the screen and the actual average diameter.

a. Instantaneous Average Particle Velocity, $U(t)$. The location of each particle was measured (axial direction only) frame by frame. Particle velocity between two consecutive frames was determined as

$$U_i(t) = \frac{\ell_i[(n+1)\Delta t] - \ell_i(n\Delta t)}{\Delta t} \frac{D_p}{D_{ps}}, \quad \Delta t = \frac{1}{f_{ps}}, \quad (4)$$

where

$U_i(t)$ = the velocity of the i th particle;

$\ell_i(n\Delta t)$ = the location of the i th particle at the n th frame, on the screen;

$\ell_i[(n+1)\Delta t]$ = the location of the i th particle at the $n+1$ st frame;

f_{ps} = the film speed, frames per second;

D_p = the actual average diameter of the particle;

and

D_{ps} = the average diameter of particles on the screen.

The instantaneous average particle velocity is

$$U(t) = \frac{\sum_{i=1}^m U_i(t)}{m}.$$

b. Average Travel Distance of Particles, $S_p(t)$. If all particles on the internal surface in the vicinity of an observed location are assumed to behave as do the particles actually observed at the surface, the average travel distance of particles, $S_p(t)$, is obtained by carrying out the integration of average particle velocity $U(t)$ with time,

$$S_p(t) = \int_0^t U(t) dt.$$

c. Instantaneous Mean Residence Time, $\tau(t)$. The mean residence time of all particles at the heater surface at a given time, t , is calculated from the instantaneous average velocity profile as follows:

(1) The average time that the particles stay at the surface after time t , $\tau_1(t)$, is determined: if one particle located at a distance x_1 from the top of the heater (see Fig. 5) is considered, the time required for the particle to leave the heater will be determined by finding the upper limit of integration of $U(t)$ for time t ,

$$x_1 = \int_t^{\tau_{11}} U(t) dt = L_1(x_1, t); \quad (5)$$

Fig. 5. Method of Calculating Mean Residence Time

$$\tau_{11}^1(t) = L_1^{-1}(x_1, t). \quad (6)$$

Carrying out this operation at all positions on the heater surface gives the average time at which particles leave the heater surface,

$$\tau_1^1(t) = \frac{1}{l} \int_0^l L_1^{-1}(x, t) dx, \quad (7)$$

where l is heater length. Therefore, this time period is

$$\tau_1(t) = \tau_1^1(t) - t. \quad (8)$$

(2) The average time that particles have remained on the surface until time t , $\tau_2(t)$, is determined by operating the same procedure backward. That is,

$$x_2 = \int_{\tau_{22}^1}^t U(t) dt = L_2(x_2, t); \quad (9)$$

$$\tau_{22}^1(t) = L_2^{-1}(x_2, t); \quad (10)$$

$$\tau_2^1(t) = \frac{1}{\ell} \int_0^{\ell} L_2^{-1}(x, t) dx. \quad (11)$$

Therefore

$$\tau_2(t) = \tau_2^1(t) - t. \quad (12)$$

The total residence time $\tau(t)$ will be

$$\tau(t) = \tau_1(t) - \tau_2(t). \quad (13)$$

By the manner described above, the residence time could be extrapolated to obtain $\tau(t)$ for a heater larger than the field of view.

d. Average Residence Time of Particles, $\bar{\tau}$. The average residence time over one cycle of pulsation can be obtained by using Eq. 13. However, taking the average value of instantaneous mean residence time over the pulse period is not appropriate since the residence-time distribution for a number of particles should be considered. The particle flux to the heater surface, N , between the time t and $t + \Delta t$ will be

$$N = m \frac{\Delta t}{\tau(t)}, \quad (14)$$

where m is a constant. Therefore, the average residence time over one cycle pulsation can be expressed as

$$\bar{\tau} = \frac{\sum \left[m \frac{\Delta t}{\tau(t)} \cdot \tau(t) \right]}{\sum m \frac{\Delta t}{\tau(t)}} = \frac{\sum \Delta t}{\sum \frac{\Delta t}{\tau(t)}}. \quad (15)$$

For continuous distribution, Eq. 15 can be rewritten in an integral form as

$$\bar{\tau} = \frac{t_p}{\int_0^{t_p} \frac{1}{x(t)} dt}, \quad (16)$$

where t_p is a period of one cycle of pulsation.

Calculations are carried by a digital computer.

5. Residence Time in Fluidized Beds

The motion pictures taken by me and those borrowed from Brusenback¹⁸ were analyzed to obtain the average particle-residence time. Brusenback¹⁸ determined the residence time at the heater surface to be

$$\bar{\tau} = \frac{\ell P}{|\bar{U}|}, \quad (17)$$

where P is a persistence factor, which is supposed to be less than unity by his definition, and $|\bar{U}|$ is the average value of absolute particle velocity.

Fig. 6. Some Patterns of Particle Motion in a Fluidized Bed

In a fluidized bed, the behavior of solid particles on a boundary surface is such that a particle moves along the boundary surface in one direction, stops, and stays there for a certain time and then moves again in the same or different direction as illustrated in Fig. 6. Equation 17 does not take account of this effect. Therefore, a different way of determining the average residence time is used here. Frame by

frame, tracer particles crossing the boundary of the field of view are followed until they leave by either of the boundaries. Thus, the residence times of particles (i.e., the times during which they remain within the boundaries) are measured at each time interval, no matter what the pattern of the particle motion is. In this way, the instantaneous residence time, $\tau(t)$, as a function of time is developed.

Assuming that the particle population at the heater surface in a particulate phase does not change, input of the particles to the heater surface at time t is expressed as Eq. 14. Therefore, the average particle-residence time, corresponding to the residence time distribution versus number of particles, is obtained from Eq. 15. Since the field of view is 0.4 in., whereas a heater length is 0.5 in., measured instantaneous residence time is multiplied by a factor of 1.25.

6. Heat-transfer Coefficient

The heat-transfer coefficient is obtained from the bed temperature measured by an immersed thermocouple and the heater temperature measured by a thermocouple imbedded on the heater surface as

$$h = \frac{Q}{(T_s - T_b) A_h}, \quad (18)$$

where

T_s = surface temperature,

T_b = bed temperature,

A_h = heater surface area, and

Q = heat input.

Heat input is obtained from the amperage and voltage of the heater circuit.

Four sizes of glass beads and one size each of aluminum and copper shot, as listed in Table I, were used in the heat-transfer experiments. Various pulsing conditions were tested to see the effect of on- and off-period for these six kinds of particles. Heater length, heater position, and static-bed height were taken as variables to explore the heat-transfer characteristics in pulsed beds. Also, air, carbon dioxide, and helium were used as throughput gas in the experiments. The combinations of these experimental variables are listed in Table II.

TABLE II. Combinations of Experimental Variables

Particle:	a) 580- μ m glass beads; b) 301- μ m glass beads; c) 138- μ m glass beads; d) 73- μ m glass beads; e) 292- μ m aluminum shot; f) 313- μ m copper shot;			
Gas:	g) air; h) carbon dioxide; i) helium;			
Heater length:	j) 0.5 in.; k) 2.0 in.; l) 4.0 in.;			
Heater position:	m) 1 in.; n) 3 in.; o) 6 in.;			
Static-bed height:	p) 4 in.; q) 8 in.; r) 12 in.			
On-period	Off-period	Combination		
0.125 sec	0.375 sec	(a-g-j-o-r), (a-g-j-n-r), (a-g-l-o-r), (a-g-j-n-q),	(b-g-j-o-q), (a-g-j-o-q), (a-g-l-n-r), (f-g-j-o-q),	(a-g-j-m-b), (a-g-k-o-r), (a-g-j-n-p), (e-g-j-o-q)
0.2 sec	0.4 sec	(c-g-j-o-r), (c-h-j-o-r), (c-g-h-n-q)	(c-g-k-o-r), (c-i-j-o-r),	(c-g-l-o-r), (c-g-l-n-r),
0.2 sec	0.6 sec	(c-g-j-o-r), (c-g-l-n-r), (c-h-j-o-r),	(c-g-k-o-r), (c-g-j-m-r), (c-i-j-o-r)	(c-g-l-o-r), (c-g-j-n-r),
0.25 sec	0.25 sec	(a-g-j-o-r), (a-g-j-n-r), (a-g-l-o-r), (f-g-j-o-q),	(b-g-j-o-q), (a-g-k-n-r), (a-g-j-n-p), (e-g-j-o-q)	(a-g-j-m-r), (a-g-k-o-r), (a-g-j-n-q),
0.25 sec	0.5 sec	(d-g-j-o-r), (a-g-k-o-r), (a-g-j-n-p)	(a-g-j-m-r), (a-g-l-o-r),	(a-g-k-n-r), (a-g-l-n-r),
0.25 sec	0.75 sec	(a-g-j-o-q), (d-g-j-o-r),	(b-g-j-o-q), (f-g-j-o-r),	(c-g-j-o-r), (e-g-j-o-q)
0.375 sec	0.375 sec	(a-g-j-o-q)		
0.5 sec	0.5 sec	(c-g-j-o-r), (c-g-j-m-r), (c-g-j-n-q),	(c-g-k-o-r), (c-g-j-n-r), (c-g-d-n-r),	(c-g-l-o-r), (c-g-j-n-p), (c-g-l-n-q)
0.5 sec	1.0 sec	(d-g-j-o-r)		
Conventional fluidization		(a-g-j-o-r), (a-g-j-o-q), (a-g-j-n-p), (c-g-l-o-r), (c-g-j-m-r), (a-g-j-n-q), (c-h-j-o-r), (f-g-j-o-q),	(b-g-j-o-q), (a-g-j-n-r), (a-g-l-o-r), (a-g-l-n-r), (c-g-j-n-r), (c-g-j-n-p), (c-i-j-o-r), (e-g-j-o-q),	(c-g-j-o-r), (a-g-k-o-r), (c-g-k-o-r), (c-g-l-n-r), (a-g-j-m-q), (c-g-j-n-q), (c-g-l-n-q), (d-g-j-o-r)

V. THEORETICAL DEVELOPMENT, EXPERIMENTAL RESULTS, AND DISCUSSION

A. Bed Behavior

1. Minimum Fluidization Velocity and Minimum Bubbling Velocity

Table III lists the minimum fluidization velocities and minimum bubbling velocities for various particles.

TABLE III. Minimum Fluidization and Bubbling Velocities

Particle	Average Diameter, μm	v_{mf} , ft/sec	v_{mb} , ft/sec
No. 1 glass beads	580	0.70	0.90
No. 2 glass beads	301	0.254	0.258
No. 3 glass beads	138	0.068	0.082
No. 4 glass beads	73	-	-
Aluminum shot	293	-	0.26
Copper shot	323	-	1.1

2. Pressure-drop Patterns

Fig. 7. Pressure-drop Patterns in a Pulsed Bed of 580- μm Glass Beads for Pulsing Conditions Providing Good Particle-motion Characteristics (Integral gas velocity: 0.843 ft/sec; On-period: 0.125 sec; Off-period: 0.375 sec)

Figure 7 shows the pressure-drop patterns of 580- μm glass beads for a pulsing condition ($v_0 = 0.843$ ft/sec, $v = 3.37$ ft/sec, on-period = 0.125 sec, off-period = 0.375 sec) that provides good particle-motion characteristics. In this condition, the particles are essentially never at rest. As the gas is introduced, when the pressure drop reaches the weight of particles, the bed starts moving upward. The pressure drop continues to increase, breaking up the geometrical configuration of particles in the packed condition until the bed is loosened. As the bed is loosened, the pressure drop decreases. This is similar to the pressure-drop pattern of fluidized beds when gas flow is initially introduced. In a pulsed-bed system, the gas stream is shut off before the bed reaches the state of fluidization. However, particles are still moving up at this moment, which causes the negative gauge pressure. As particles fall, the pressure drop again increases, and as the gas leaves the bed,

the pressure drop decreases. As soon as the particles settle completely, another gas pulse is introduced. The bed is fully controlled by the pulsing operation.

Fig. 8. Pressure-drop Patterns in a Pulsed Bed of 580- μ m Glass Beads Where On-periods Are Excessive for Maintaining Controlled Pulse Characteristics (Integral gas velocity: 0.835 ft/sec; On-period: 0.875 sec; Off-period: 0.235 sec)

Figure 8 shows the pressure-drop pattern for 580- μ m glass beads in which the pulsing conditions ($v_0 = 0.835$ ft/sec, $v = 1.06$ ft/sec, on-period = 0.875 sec, off-period = 0.235 sec) have on-periods that are excessive for maintaining controlled pulse characteristics. At the beginning of pulsation, bed behavior is similar to that described in the previous paragraph, but the peak of pressure drop is lower due to the lower pulsed-gas velocity. The bed approaches fluidization because of the long on-period, during which bubbles appear in the bed and the effects of bubbles and slugs dominate the effect of pulsation.

Figure 9 shows the pressure-drop pattern for an excessively long off-period ($v_0 = 0.835$ ft/sec, $v = 1.55$ ft/sec, on-period = 0.875 sec, off-period = 0.75 sec), which allows the particles to stay stationary for some time after the bed settles. The on-period pattern is similar to that shown in Fig. 6.

Figure 10 shows the pressure-drop pattern for 301- μ m glass beads with on- and off-periods of 0.125 and 0.375 sec, respectively, and an integral velocity of 0.281 ft/sec. The pattern is almost the same as that of the 580- μ m glass beads shown in Fig. 7, but the maximum pressure drop is smaller due to the smaller pulsed-gas velocity. The settling rate of the bed seems to be slower than that of 580- μ m glass-bead beds in spite of lower gas velocity due to greater resistance of the beds. Other pulsing conditions also provide patterns similar to those of 580- μ m glass-bead beds. For these two sizes of glass beads, the pressure-drop pattern for each pulse is quite reproducible and regular, as may be seen in Figs. 7-10.

Fig. 9. Pressure-drop Patterns in a Pulsed Bed of 580- μ m Glass Beads Where Off-period Is Too Long (Integral gas velocity: 0.835 ft/sec; On-period: 0.875 sec; Off-period: 0.75 sec)

Fig. 10. Pressure-drop Patterns in a Pulsed Bed of 301- μ m Glass Beads

Figures 11-13 show pressure-drop patterns for 138- μ m glass-bead beds. Figure 11 shows a pressure-drop pattern in which the pulsing conditions ($v_0 = 0.330$ ft/sec, on-period = 0.22 sec, off-period = 0.53 sec) provide relatively good pulsing-bed movement for this particle size. During the on-period, a large bubble or slug goes through the bed, which causes the pressure fluctuation during the on-period. At the end of the off-period, the bed settles completely. The effect of pulsation is fully retained by this pulsing condition. Figure 12 shows a pressure-drop pattern in which the pulsing conditions ($v_0 = 0.304$ ft/sec, on-period = 0.22 sec, off-period = 0.38 sec) do not include a long enough off-period. During the on-period, the bed behaves as the bed in Fig. 11 does; however, the off-period is too short to allow the bed to settle before the next pulse is introduced.

Fig. 11. Pressure-drop Patterns in a Pulsed Bed of 138- μ m Glass Beads for Pulsing Conditions Providing Good Particle-Motion Characteristics

Fig. 12. Pressure-drop Patterns in a Pulsed Bed of 138- μ m Glass Beads Where Off-period Is Too Short

Fig. 13

Pressure-drop Patterns in a Pulsed Bed of 138- μ m Glass Beads Where On-period Is Too Long

With the pulsing conditions in Fig. 13 ($v_0 = 0.314$ ft/sec, on-period = 0.375 sec, off-period = 0.375 sec), the on-period is too long, which may cause the system to be unstable as a pulsed bed. During the on-period, the bed approaches the fluidized state.

Figures 14 and 15 show pressure-drop patterns for 73- μ m glass-bead beds. Figure 14 shows the pressure-drop pattern for the pulsing conditions of $v_0 = 0.0754$ ft/sec, on-period = 0.25 sec, and off-period = 0.75 sec; the settling rate of the bed is extremely slow, and the bed does not settle even for 0.75 sec. Figure 15 is for the pulsing conditions of $v_0 = 0.071$ ft/sec, on-period = 0.25 sec, and off-period = 0.25 sec. For this pulsing condition, the effect of pulsing operation is nearly sacrificed. In all the pulsing conditions tested, the first sharp peak was not observed for this size glass bead.

Fig. 14. Pressure-drop Patterns in a Pulsed Bed of 73- μ m Glass Beads with $v_0 = 0.0754$ ft/sec, On-period = 0.25 sec, and Off-period = 0.75 sec

Fig. 15. Pressure-drop Patterns in a Pulsed Bed of 73- μ m Glass Beads with $v_0 = 0.0751$ ft/sec, On-period = 0.25 sec, and Off-period = 0.25 sec

As the particle size decreases, the response of pressure drop to changes in the gas rate becomes slower, reflecting the predominance of interparticle forces over the hydrodynamics.

3. Maximum Pressure Drops

Maximum pressure was chosen to characterize the pressure drop in pulsed beds, since the average pressure drop depends mainly on the off-period. If the off-period is long, the average pressure drop is a very small value, no matter what the pressure drop is during the on-period. This situation may give the wrong impression of the effect of pulsation. The maximum pressure drop, however, depends entirely on pulsed-gas velocity and also may give an idea of bed movement.

In pulsed beds, the maximum pressure drop ($\Delta P_{\max}$) usually occurs immediately after the gas is introduced. Figure 16 shows the

Fig. 16. Maximum Pressure Drops in Pulsed, Fluidized, and Packed Beds

relationship between maximum pressure drop and pulsed-gas velocity for glass beads. The ordinate is a dimensionless maximum pressure drop, $\Delta P_{\max}/(W/A)$, and the abscissa is a dimensionless pulsed-gas velocity, v/v_{mf} , where $\Delta P_{\max}$ is the maximum pressure drop, W is the bed weight, A is the cross-sectional area of the column, v is the superficial pulsed-gas velocity based on the on-period of the pulse cycle, and v_{mf} is the superficial velocity at incipient fluidization. Line A represents the data for fluidized beds, lines B for pulsed beds, and line C for packed beds. The experimental data appear in Appendix A.

For each pulsed-bed case, when the gas velocity is greater than the incipient fluidization velocity, the maximum pressure drop seems to have a linear relationship with pulsed-gas velocity (within $\pm 10\%$ error) and appears to be independent of the pulsing conditions. At the same dimensionless gas velocity, the maximum pressure drop increases with particle size (D_p , in μm) and may be represented by

$$\frac{A\Delta P_{\max}}{W} = 1.0 + 2.02 \times 10^{-2} \left(\frac{D_p}{100} \right)^{1.675} \left(\frac{v}{v_{mf}} - 1 \right). \quad (19)$$

4. Bed Expansion and Bed Movement

The first half of this section discusses bed expansion and pulsed-bed behavior with various pulsing conditions; the second half presents predictions of bed movement.

a. Qualitative Discussion of Bed Expansion and Bed Behavior.

Bed expansions are visually observed for both pulsed and fluidized beds. Data on the bed-expansion ratio (maximum bed height/static bed height) as a function of pulsed-gas velocity are given in Fig. 17 for 580- μm glass beads to show the effect of gas velocity. The pulsing conditions with short on-periods give a lower expansion ratio than that of a fluidized bed at an equivalent pulsed-gas velocity. Under these conditions, the bed behaves as though it were in plug flow, and the bed density is quite high. For 301- μm glass beads, the pulsing conditions with on-periods less than 0.5 sec give a lower expansion ratio than that of a fluidized bed at the same pulsed-gas velocity (as shown in Fig. 18). Under these conditions, bubbles have a minor effect on bed movement. In both Figs. 17 and 18, at the same pulsed-gas velocity bed-expansion ratios increase with on-period.

Fig. 17. Bed-expansion Ratio vs Pulsed-gas Velocity for 580- μ m Glass Beads

308-1949 Rev. 1

Fig. 18. Bed-expansion Ratio vs Pulsed-gas Velocity for 301- μ m Glass Beads

308-1948 Rev. 1

Fig. 19. Bed-expansion Ratio vs Pulsed-gas Velocity for 138- μ m Glass Beads

Figure 19 shows bed-expansion ratios for beds of 138- μ m glass beads. At lower pulsed-gas velocities, all the pulsing conditions used in this investigation provide lower bed-expansion ratios than those of a fluidized bed. At gas velocities having a v/v_{mf} ratio higher than about 6 to 7, bed-expansion ratios are higher than those of fluidized beds and are somewhat scattered, since the beds do not completely settle during off-periods. Also, beds of 73- μ m glass beads showed the same tendency.

Figures 20-22 show the relationships between bed-expansion ratio and integral gas flowrate for 580- μ m glass beads. The pulsed beds give larger expansion ratios than do fluidized beds at the same gas throughput. The bed-expansion ratio appears to increase with integral gas velocity, decrease with pulse frequency (as shown in Fig. 20), and decrease with

fraction of on-period (as shown in Figs. 21 and 22). With a decrease of off-period or an extreme increase of frequency, the bed approaches the fluidized condition, as expected. The same bed-expansion characteristics

Fig. 20

Bed Expansion at Various Frequencies vs Integral Gas Velocity (Average diameter of glass beads = 580 μm)

Fig. 21
Bed Expansion at Various Off-periods vs Integral Gas Velocity (Average diameter of glass beads = 580 μm)

Fig. 22

Bed Expansion at Various Ratios of On-period to Off-period vs Integral Gas Velocity (Average diameter of glass beads = 580 μm)

are observed for all particle sizes. However, for smaller particles the explicit relationships of these characteristics become somewhat obscure. (The experimental data appear in Appendix A.)

308-1955 Rev. 1

Fig. 23. Particle-velocity Profile at 6.0- and 1.5-in. Levels (Particles: 580- μ m glass beads)

The motion of particles on a simulated heater surface were photographed at 1.5 and 6 in. above the bottom of the bed for 580- μ m glass beads. Figure 23 shows particle-velocity profiles developed from the photographs. Positive velocity means an upward motion of particle, and negative velocity a downward motion of particle. Comparison of the particle motion at the 6-in. level ($v_0/v_{mf} = 1.17$, $v_0/v_{mb} = 0.92$) with the pressure-drop pattern in Fig. 7 shows that point A in Fig. 23, where the velocity reaches a steady high value, corresponds to the point where pressure drop reaches its peak. Point B in Fig. 23, where the velocity starts to diminish, corresponds to the point at which the slope of the pressure drop changes. At point C, where the direction of particle movement changes, pressure drop is at a minimum.

In Fig. 23, comparing the velocity profiles at the 6- and 1.5-in. levels shows a discontinuity of particle motion at 1.5 in. At the same integral gas velocity, a large gas void was clearly observed at the 1.5-in. level, whereas no gas void was observed at the 6-in. level. (The experimental data appear in Appendix E.)

b. Estimation of Bed Behavior. Bed expansion depends on the pulsing conditions. For efficient operation of pulsed beds, the pulsing conditions should be chosen so that the bed contracts to its minimum fluidized-bed height (H_{mf}) at the end of the off-period. If the next gas pulse enters the system before the bed contracts to this point, the bed may assume a more or less fluidized state and may be unstable as a pulsed bed. The gas input is best cut off before the excess gas (above that required for incipient fluidization) leaves the bed. Again, if the on-period is longer than this period, the bed behaves as a fluidized bed and any advantage of a controlled pulsed bed is sacrificed. If the on-period is too long, the bed becomes unstable as a pulsed bed and starts slugging.

Assuming that the density in any continuous phase remains the same as at the fluidization point, the minimum time for excess gas to remain in the bed can be estimated from the fastest rising velocity of the first bubble for fluidized beds (based on the two-phase theory)^{31,32} for the pulsing conditions that allow the bed to settle to the minimum fluidized height. That is

$$u_b = K(v - v_{mb}) + u_{b0} \quad (20a)$$

and

$$u_{b0} = 0.711(gD_b)^{1/2}, \quad (20b)$$

where

D_b = diameter of largest bubble in system,

u_b = rising velocity of gas bubbles in a freely bubbling fluidized bed,

u_{b0} = rising velocity of identical bubble in an incipiently fluidized bed,

K = a constant,

and

g = gravitational constant.

Assuming that the behavior of bubbles is the same for fluidized and pulsed beds, the minimum time for bubbles to break through the pulsed-bed surface will be H_{mf}/u_b .

As pointed out earlier in this section, the on-period should be such that, after the gas flow is initiated, the gas input may be cut off before the excess gas leaves the bed. Hence,

$$\begin{aligned} \text{upper limit for on-period} &= \frac{H_{mf}}{u_b} + t_{fb} = \frac{H_{mf}}{K(v - v_{mb}) + u_{b0}} \\ &+ \frac{\pi D_b^3}{6(v - v_{mb}) A}, \end{aligned} \quad (21)$$

where t_{fb} is the time required to form the bubble on the distributor.

The constant K has to be determined experimentally. Davidson and Harrison³³ stated that, for large slugs, $K > 1$ because the particles falling down the wall at the sides of the slug will be bypassed. For a pulsed-bed system, K was determined to be 1.4 for four sizes of glass beads.

The bed movements were photographed, and the history of the bed height during one cycle of pulsation is shown in Figs. 24-27. Figures 24 and 25 are for pulsing conditions of 0.125 sec on, 0.375 sec off, with 8- and 12-in. bed heights, respectively. Figures 26 and 27 are for pulsing conditions of 0.25 sec on, 0.25 sec off, with 8- and 12-in. bed heights.

The particles used were 580- μm glass beads. In Fig. 24, the gas bubble breaking through the top surface was observed at the pulsed-gas velocity of 3.42 ft/sec. The upper limit of on-period from Eq. 21 is 0.123 sec. In Fig. 25 for a 12-in. bed, at the pulsed-gas velocity of 3.34 ft/sec, no gas bubble was observed. The upper limit of on-period calculated from Eq. 21 is 0.190 sec.

Fig. 24. Bed Movement for 0.125-sec On-period, 0.375-sec Off-period, and 8-in. Bed Height

Fig. 25. Bed Movement for 0.125-sec On-period, 0.375-sec Off-period, and 12-in. Bed Height

Fig. 26. Bed Movement for 0.25-sec On-period, 0.25-sec Off-period, and 8-in. Bed Height

Fig. 27. Bed Movement for 0.25-sec On-period, 0.25-sec Off-period, and 12-in. Bed Height

In Fig. 26, bubbles were also observed at the pulsed-gas velocity of 2.10 ft/sec. The upper limit calculated is 0.21 sec. For a 12-in. bed at a 1.16-ft/sec pulsed-gas velocity, the upper limit calculated is 0.28 sec. Equation 21 does not seem to be applicable for 138- μm glass beads, since the bed does not settle sufficiently during the off-period tested.

For those cases in which the on-period and off-period provide stable or satisfactory pulsed-bed conditions, we may apply the two-phase theory for a pulsed bed to estimate the maximum expansion ratio. If the on-period is shorter than the time required for the first bubble to break through the top of the bed, all excess gas input during this period exists in the bed as bubbles or slugs.

As seen in Fig. 23, this excess gas initially creates a gas phase at the bottom of the bed and consequently lifts up the bed. As this gas bubble or slug rises, it disperses into the continuous particle phase. Therefore, the stroke of the bed movement is estimated as

$$S_b = (v - v_{mb}) t_{on} \quad (22)$$

$$= v_0(t_{on} + t_{off}) - v_{mb}t_{on} \quad (23)$$

where

S_b = the bed stroke.

Figure 28 compares experimental values of S_b obtained from motion pictures and calculated values for 580- and 138- μ m glass beads.

Fig. 28. Comparison of Predicted Bed Stroke with Experimental Data

As seen in Figs. 24-27, the velocity of the descending bed seems to be constant (the slope of the descending curve in figures) for piston-like bed behavior. The optimum value of the off-period could be estimated as

$$t_{off} = S_b / U_{db} \quad (24)$$

where U_{db} = the velocity of the descending bed surface. For 580- μ m glass beads within 10% error, U_{db} is 9.2 in./sec.

Experimental data for this section are presented in Appendix C.

B. Mechanism for Heat Transfer from Wall to Gas-Solid Bed

In an attempt to estimate the heat-transfer coefficient at a heater in a gas-solid system such as a fluidized or pulsed bed, two considerations are encountered. The first is how to regard the dependency of the heat-transfer rate on particle residence time at the heater surface. The second is how to correlate the particle residence time to the bed behavior, taking into account the gas voidage of the system. This section discusses mainly the first problem. A model for heat transfer from wall to gas-solid-particle bed is proposed. This model is later used to estimate the heat-transfer coefficient in a pulsed bed.

1. Discussion of Models Proposed in the Literature

A survey of the current literature disclosed the following proposed mechanisms:

a. A Thin-fluid-film Resistance Model.^{10,11,14,15,16} This model does not take into account the effect of the thermal properties of particles--especially heat capacity--which are believed to be significant.

b. Packet Model.^{12,14,16} This model may be reasonable and acceptable for very small particle size and long particle-residence time; however, the discrepancy is significantly large for larger particles and short residence time. This model gives much higher values than those experimentally determined.

For effective thermal conductivity, Swift's³⁴ model is recommended. By taking account of porosities greater than those found in a minimum-fluidized bed, his model is suitable for the general void fraction $\epsilon > \epsilon_0$. Swift expressed the effective thermal conductivity of the bed as

$$k_{em} = 1.813 \frac{k_g k_s}{k_s - k_g} \left(\frac{k_s}{k_s - k_g} \ln \frac{k_s}{k_g} - 1 \right) + 0.035 k_g, \quad (25)$$

where k_{em} = the effective thermal conductivity. If the distance between particles is separated by ηD_p and the distance between the particle and the wall is $\eta D_p/2$, Eq. 25 is changed to

$$k_{em,\eta} = \frac{1.813}{1 + \eta} \frac{k_g k_s}{k_s - k_g} \left[\frac{(1 + \eta) k_s}{k_s - k_g} \ln \frac{(1 + \eta) k_s}{k_g + \eta k_s} - 1 \right] + \left[1 - \frac{0.845}{(1 + \eta)^2} \right] k_g \quad (26)$$

where

$$\eta = \frac{0.845}{(1 - \epsilon)^{1/3}} - 1.$$

Dependency of the effective thermal conductivity obtained from Eq. 26 on void fraction for the glass bead and air system is plotted in Fig. 29.

Fig. 29. Dependency of Effective Thermal Conductivity on Void Fraction

The "packet" model especially fails at short residence time, that is, at the higher gas rates in Patel's data.²⁸ This tendency qualitatively favors the idea of change in effective thermal conductivity. However, the drawback of this model is that the value of η may have to be changed with the gas velocity.

c. Jacob and Osberg's Model.¹³ This is a rather empirical model and also does not take account of the effect of particle size.

d. Particle Convective-transfer Model.^{21,22} The model of Ziegler, Koppel, and Brazelton²¹ does not consider the contribution of the region beyond the first layer of particles to the heat transfer. Also, it neglects the relatively high resistance of the gas film next to the surface.

Wasmund and Smith's model²² has some difficulties relative to particle motion. For example, in their model, particles do not stay at a heater surface; however, in a fluidized system, particles move along the boundary surface.

e. Contact-resistance Model.^{20,28} The contact resistance between particles and the heater surface is determined from the steady-state process, which is unrealistic since the gas phase between a heater and the particles is considered to be more important for shorter residence time, as stated by Ernst.¹⁴

f. Inhomogeneous Model.^{18,23-27} The models that considered the inhomogeneity of the gas phase and solid particles are very reasonable and agree well with experimental results. The model of Botterill *et al.*²³⁻²⁵ may be good for a short residence time, since it only considers the penetration of heat to the second layer of particles. This model assumes no rotational movement of particles on the surface, which does not seem to be true. Brusenback's model¹⁸ assumes a uniform temperature profile inside a particle, a reasonable assumption. However, the path of heat flow in his model is artificially assigned a conical pattern. The number of particles for heat penetration was limited to four, because of the complexity of the equation for computations.

2. Proposed Model

Because of the complexity of the bed behavior, it is virtually impossible to propose the heat-transfer mechanism in a fluidized system. However, we may safely say that the heat-transfer mechanism can be discussed qualitatively and be represented by a model considering the time-averaged motion of the particles. From the models proposed in the literature, it seems necessary to consider the bed as inhomogeneous, consisting of gas phase and solid particles. For short particle-residence times, a thin gas film next to the heater surface has an important role in heat transfer; for long residence times, the "packet" model seems to agree with experimental data. Based on these facts, the following model for the heat-transfer mechanism between particle and heater surface is proposed.

The assumptions are as follows:

a. N particles are arranged in a line perpendicular to the heater surface.

b. On a time-averaged basis, there exists a small gas gap, ηD_p , between two particles, as well as between the heater surface and a particle.

c. The heat capacity of the gas phase is negligible.

$$\bar{q}_m = \frac{\pi k_{g,m} D_p}{2} \left(\ln \frac{2+\eta}{\eta} - 1 \right) (T_{p,m-1} - T_{p,m}), \quad (28b)$$

and

$$\bar{q}_N = \pi k_{g,N} D_p \left(\ln \frac{2+\eta}{\eta} - 1 \right) (T_{p,N} - T_b). \quad (28c)$$

From the heat balance,

$$\frac{\pi D_p^3}{6} \rho C_p \sum_{i=1}^N \frac{dT_{p,i}}{dt} = B_0 (T_s - T_{p,1}) - B_N (T_{p,N} - T_b), \quad (29a)$$

$$\frac{\pi D_p^3}{6} \rho C_p \sum_{i=2}^N \frac{dT_{p,i}}{dt} = B_1 (T_{p,1} - T_{p,2}) - B_N (T_{p,N} - T_b), \quad (29b)$$

and

$$\frac{\pi D_p^3}{6} \rho C_p \sum_{i=N}^N \frac{dT_{p,i}}{dt} = B_{N-1} (T_{p,N-1} - T_{p,N}) - B_N (T_{p,N} - T_b), \quad (29c)$$

where

$$B_0 = \pi k_{g,0} D_p \left(\ln \frac{1+\eta}{\eta} - 1 \right), \quad (30a)$$

$$B_1 = \frac{\pi k_{g,1} D_p}{2} \left(\ln \frac{2+\eta}{\eta} - 1 \right), \quad (30b)$$

$$B_{N-1} = \frac{\pi k_{g,N-1} D_p}{2} \left(\ln \frac{2+\eta}{\eta} - 1 \right), \quad (30c)$$

and

$$B_N = \pi k_{g,N} D_p \left(\ln \frac{2+\eta}{\eta} - 1 \right). \quad (30d)$$

Assuming a cubic geometrical configuration of particles, a heat-transfer coefficient is expressed as

$$h = \frac{\bar{q}_0}{(T_s - T_b) D_p^2}. \quad (31)$$

3. Discussion of Assumptions

a. Assumption a. This assumption may be reasonable for the loosest configurations encountered at the incipient fluidized-bed condition.

b. Assumptions b and d. The motion of marked tracer particles on the internal surface was photographed to see the rotational motion of particles. The results are shown in Fig. 31 (average particle size is $580\ \mu\text{m}$). Particle motion was observed

Fig. 31. Rotation of Particles in Fluidized Bed

at two gas velocities, $v_0/v_{mb} = 1.32$ and 1.67 . The upper and lower lines represent the maximum and minimum observed rotations, and the middle line the average rotation. The ordinate is the number of particle revolutions per second. The abscissa is the value of particle velocity, U_p , divided by the circumference of the sphere. Each particle rotates rather freely and independently. However, rotational speed tends to increase with the particle velocity. For 0.5-in. heaters, particles may rotate 9 to 22 times on the heater surface, no matter what the particle residence time is. Particles skip around on the heater.

Therefore, it is reasonable to assume some gas gap between the particle and the heater surface. The existence of a gas gap between particles on a time-averaged basis may be reasonably assumed since each particle rotates rather freely. The nonuniform rotation of particles verifies that particles sometime contact other particles and sometimes are separated.

Considering the rotation of particles and the fact that the thermal conductivity of the solid particles is much higher than that of the gas phase, the assumption of a uniform temperature profile in a particle is quite reasonable.

c. Assumption c. Comparison of the heat capacity of the gas phase to that of a solid particle may allow this assumption.

d. Assumption e. This assumption may follow Assumption c since the heat carried by the gas phase is negligible. Also, this assumption simplifies the computation.

4. Comparison of Proposed Model with Data

In accordance with the above assumptions, the heat-transfer coefficients were numerically calculated for differential time intervals of

0.002 sec using a digital computer. The value of N , the number of particles in the line of transfer, was chosen as 15 in all calculations. This is considered to be satisfactory, since the heat does not penetrate beyond the 15th particle, even for relatively long residence times.

To demonstrate the feasibility of this model, the following discussion compares results calculated from the model with the data from Botterill *et al.*²⁴ in moving beds, the data of Botterill *et al.*²⁴ and Patel²⁸ in a stirred fluidized bed, and current experimental data in fluidized beds.

a. Moving Bed. Figures 32-34 compare the experimental data in a moving bed and a stirred bed by Botterill *et al.*^{24,25} with results calculated from the model using 0.005 and 0.010 for the value of η . The ordinate is hD_p , and the abscissa is t/D_p^2 .

Fig. 32. Comparison of Model with Data for Air-Glass-bead System

Fig. 33. Comparison of Model with Data for Air-Copper-shot System

Fig. 34

Comparison of Model with Data for Helium-Glass-bead and Carbon Dioxide-Glass-bead Systems

308-1947 Rev. 1

The air-glass-bead system is shown in Fig. 32, air-copper-shot system in Fig. 33, helium-glass-bead and carbon dioxide-glass-bead systems in Fig. 34. For the air-glass-bead, air-copper-shot, and carbon dioxide-glass-bead systems, experimental values agree well with the calculated lines.

However, for the helium-glass-bead system, experimental values are far below the calculated line. This tendency is also observed in the model of Botterill *et al.*

b. Fluidized Bed. Since the bed expansion is greater in a fluidized bed than in a moving bed, the value for η was chosen to be 0.015. Table IV compares the calculated values with Patel's experimental data for 580- μm glass beads and air in stirred fluidized beds.

TABLE IV. Comparison of Model with Data

Particle Residence Time, τ , sec	Heat-transfer Coefficient, Btu/(hr)($^{\circ}\text{F}$)(ft ²)	
	Experimental Value	Calculated Using Model
0.4	71.8	71.7
0.7	64.7	64.8
1.4	57.3	53.3
1.7	44.3	47.0

For 301- μm glass beads, motion pictures taken at an internal surface by Brusenback¹⁸ were used to compare the experimentally determined heat-transfer coefficients with values calculated from the model. In the heat-transfer experiment, the conditions were made similar to those under which the pictures were taken; that is, the bed height was set at 6 in., and a 0.5-in. heater was placed 3 in. above the bottom of the bed.

The instantaneous particle-residence time is shown in Fig. 35 as an example. (The experimental data appear in Appendix B.)

From this graph, the average particle-residence time for the total number of particles crossing the field of view was calculated using Eq. 15. In Fig. 35, the discontinuity of the lines is due to either no movement of the particles or gas bubbles. Therefore, during these periods, no particle input to the heater surface takes place. The heat-transfer coefficient is obtained as

$$h = h_c(\bar{\tau})f_N, \quad (32)$$

where $h_c(\bar{\tau})$ is the calculated heat-transfer coefficient corresponding to the residence time $\bar{\tau}$, and f_N is the fraction

Fig. 35. Instantaneous Residence Time of Particles in a Fluidized Bed

of time during which particle input to the heater takes place. The factor f_N is evaluated as the ratio of the total time represented by the solid lines in Fig. 35 to the total observed time. Instead of the average residence time, $\bar{\tau}$, the heat-transfer coefficients are calculated using the instantaneous residence time; that is,

$$h = \frac{1}{t} \int_0^t h(\tau) d\theta. \quad (33)$$

These two methods are referred to as the average-time method and the instantaneous method, respectively. The results are given in Table V.

TABLE V. Predicted Heat-transfer Coefficients

v_0/v_{mb}	$\bar{\tau}$	$h_c(\bar{\tau})$, Btu/(hr)(°F)(ft ²)	f_N	Heat-transfer Coefficient, h_p , Btu/(hr)(°F)(ft ²)	
				Average Time Method	Instantaneous Method
1.11	0.220	121.5	0.608	73.9	62.0
1.38	0.119	138.4	0.745	102.5	95.8
1.51	0.074	146.9	0.772	113.8	112.8
2.12	0.044	154.0	0.826	127.3	124.1
3.24	0.041	155.4	0.750	116.5	113.2

Fig. 36. Comparison of Model with Data for 301- μ m Glass Beads

Figure 36 compares the experimental and calculated values. (The experimental data appear in Appendix D.) The calculated values using the residence time reported in Brusenback's thesis¹⁸ are added. The average-time method provides slightly higher values than does the instantaneous method; however, both are in good agreement with the data, except at the point $v_0/v_{mb} = 3.24$. Brusenback's method of determining the residence time does not represent the rapid decrease in heat-transfer coefficients at lower gas velocities.

Since the physical properties of aluminum shot are almost the same as those of glass beads, the residence-time data used for glass beads were used to see the effect of the particle thermal properties. The result is shown in Fig. 37.

It has been seen that the proposed model can well represent the experimental data with $\eta = 0.005$ to ~ 0.010 for moving beds and with $\eta = 0.015$ for a fluidized-bed system. The merit of this model is that the numerical calculation is much simpler than for Botterill's model.

308-1957 Rev. 1

Fig. 37. Comparison of Model with Data
for 291- μ m Aluminum Shot

stroke and proposed heat-transfer model is also discussed. (The experimental data appear in Appendix D.)

1. Effect of Particle Size and Pulsing Conditions

Figure 38 shows the relation between heat-transfer coefficients and gas throughputs for various pulsing conditions as well as for a fluidized bed for a 580- μ m-average-diameter glass-bead-air system. The heater length is 0.5 in., and the heater is 6 in. above the bottom of the bed.

The heat-transfer rate from an internal surface to a pulsed bed increases with the gas throughput, reaches a maximum value, and then decreases as gas voidage increases, no matter what the pulsing condition is. These heat-transfer, gas-throughput characteristics are much like those of a fluidized bed. However, the sharp increase in heat-transfer rate occurs at lower gas throughputs in pulsed beds than in fluidized beds. In fluidized beds, this increase occurs at the minimum bubbling velocity. For large particle sizes, this region of rapid heat-transfer increase occurs for pulsed beds at gas throughputs far below the minimum fluidizing value.

For the pulsing conditions of 0.125 sec on, 0.375 sec off, a heat-transfer

C. Heat Transfer in Fluidized and Pulsed Beds

This section discusses the heat-transfer characteristics of a pulsed bed, with attention to comparisons with heat transfer in a fluidized bed. Operating variables considered are particle size, pulsing conditions, heater position in the bed, static-bed height, heater length, and thermal properties of gas and solid particles. The method of estimating the heat-transfer coefficient in a pulsed bed using the predicted bed

308-1907 Rev. 1

Fig. 38. Heat-transfer Coefficients vs
Gas Velocity for 580- μ m-
diam Glass Beads and 0.5-in.-
long Heater

coefficient is obtained in the pulsed bed equal to the maximum in the fluidized bed at only half the gas throughput. For this pulsing condition, as gas rates are increased above this point the heat transfer continues to increase. The maximum pulsed-bed heat-transfer rate observed is 15% greater than the maximum of the fluidized bed. For 0.125 sec on, 0.375 sec off, the maximum point was not reached because the gas throughput was

limited by the pressure limitation of the system. Therefore, the actual maximum heat-transfer value in a pulsed bed could be higher than that reported (see Fig. 38). For this particle size, the pulsing condition of 0.125 sec on, 0.375 sec off, seems to offer the best heat-transfer rate at any given gas velocity up to the system limit.

308-1906 Rev. 1

Fig. 39. Heat-transfer Coefficients vs Gas Velocity for 301- μ m-diam Glass Beads and 0.5-in.-long Heater

Figure 39 shows heat-transfer coefficients for a 301- μ m glass-bead-air system and a 0.5-in. heater in relation to gas throughput for various pulsing conditions and for a fluidized bed. For 301- μ m glass

beads, as for 580- μ m glass beads, heat-transfer coefficients start increasing sharply when the pulsed-gas velocity (superficial gas velocity based on on-period only) is at its minimum bubbling velocity. The maximum heat-transfer coefficient in these pulsed beds is observed to be 5% greater than that of the fluidized bed.

Figures 40 and 41 show heat-transfer coefficients for 138- and 73- μ m glass beads, respectively. For these small glass beads, the advantage of the pulsed bed at integral gas velocities lower than minimum fluidization velocities, as demonstrated in Figs. 38 and 39 for larger glass beads, is not observed. However, for 138- μ m glass beads, pulsed-bed operation still provides a maximum heat-transfer coefficient 3% greater than the maximum value for the fluidized bed. For 73- μ m glass beads, the fluidized bed at very low velocities is unstable, with channels frequently forming.³⁴ However, the pulsed bed, at these low gas throughputs, provides reproducible heat-transfer rates.

Figures 42 and 43 show heat-transfer coefficients for a 580- μ m glass-bead-air system and a 2- and 4-in. heater, respectively. With the longer heater, the pulsed bed does not have the advantage of higher maximum heat-transfer values. This loss of advantage may be caused by the reduced radial movement of particles that has been observed for pulsed

beds in comparison with fluidized beds. However, the advantage of pulsed-bed operation at lower gas velocities is still quite apparent.

308-1909 Rev. 1

Fig. 40. Heat-transfer Coefficients vs Gas Velocity for 138- μm -diam Glass Beads and 0.5-in.-long Heater

308-1910 Rev. 1

Fig. 41. Heat-transfer Coefficients vs Gas Velocity for 73- μm -diam Glass Beads and 0.5-in.-long Heater

308-1942 Rev. 1

Fig. 42. Heat-transfer Coefficients vs Gas Velocity for 580- μm -diam Glass Beads and 2.0-in.-long Heater

308-1915 Rev. 1

Fig. 43. Heat-transfer Coefficients vs Gas Velocity for 580- μm -diam Glass Beads and 4.0-in.-long Heater

In summary, pulsed-bed operation is distinctly advantageous for the larger particles, which have greater minimum fluidizing velocities. The lower limit of this range for glass beads seems to be close to a 300- μm diameter. Generally, a shorter on-period for a fixed pulsed cycle provides greater heat-transfer coefficients. To obtain the maximum advantage from the use of pulsed-bed operation in a heat-transfer process--especially at low gas throughput--pulsing conditions should be such that the behavior of the bed remains piston-like without large gas slugs.

2. Effect of Heater Position

The effect of axial heater position on heat-transfer rates in pulsed and fluidized beds was investigated with a 0.5-in. heater placed 1, 3, and 6 in. above the bottom of a bed of 12-in. static height.

Figures 44 and 45 show heat-transfer coefficients at these three positions in fluidized beds for 580- and 138- μm glass-bead-air systems. In fluidized beds, the lowest heater positions generally provide the best heat-transfer rates, because of the smaller gas bubbles in this part of the bed. This effect has been reported in the literature.¹⁷ The exception to this condition occurs at gas rates just above the minimum fluidization velocity, where small bubbles do not cause enough particle agitation on the heater surface at the lowest position. In pulsed beds, however, up to certain gas velocities, the position of the heater does not cause any significant differences in heat-transfer rates. This is shown in Figs. 46 and 47 for a 580- μm glass-bead-air system with pulsing conditions of 0.125 sec on, 0.375 sec off, and 138- μm glass beads with pulsing conditions of 0.2 sec on, 0.6 sec off. However, at higher gas velocities, a heater at the lower positions gives smaller heat-transfer coefficients than those for the higher positions. This behavior, quite the opposite of that in fluidized beds, is considered to be caused by the excess gas void (gas phase). As discussed in Section V.A.4.a for the pulsed bed, the excess gas lifts up the bed during the on-period, initially creating a void, and then disperses into the solid phase as it rises. This type of behavior was seen in Fig. 23.

308-1944 Rev. 1

Fig. 44. Effect of Heater Position on Heat-transfer Coefficients in Fluidized Beds with 580- μm -diam Glass Beads and 0.5-in.-long Heater

308-1950 Rev. 1

Fig. 45. Effect of Heater Position on Heat-transfer Coefficients in Fluidized Beds with 138- μm -diam Glass Beads and 0.5-in.-long Heater

Fig. 46. Effect of Heater Position on Heat-transfer Coefficients in Pulsed Beds with 580- μ m-diam Glass Beads and 0.5-in.-long Heater

308-1956 Rev. 1

Fig. 47. Effect of Heater Position on Heat-transfer Coefficients in Pulsed Beds with 138- μ m-diam Glass Beads and 0.5-in.-long Heater

In summary, higher heat-transfer rates at lower bed positions for fluidized beds and higher heat-transfer rates at higher bed positions for pulsed beds were noted.

3. Effect of Static-bed Height

The effect of static-bed height on heat-transfer rates in pulsed and fluidized beds was observed for static-bed heights of 4, 8, and 12 in. For all these beds, a 0.5-in. heater was placed at the 3-in. position above the bottom of the bed.

Figure 48 shows the effect of static-bed height on the heat-transfer coefficient in a fluidized bed of 138- μ m glass beads. Practically no effect of static-bed height is apparent in the range of the test. Figure 49 shows heat-transfer coefficients for a pulsed bed of a 138- μ m glass-bead-air system with a pulsing condition of 0.5 sec on, 0.5 sec off. For this pulsing condition, the bed behaves very much like a fluidized bed during the on-period, and no effect of bed height on heat-transfer rate is apparent. Figures 50 and 51 present pulsing conditions that show an effect of static-bed height on heat-transfer rate. Figure 50 is for a 138- μ m glass-bead-air system with a pulsing condition of 0.2 sec on, 0.6 sec off. Figure 51 shows two pulsing conditions for 580- μ m glass beads: 0.125 sec on, 0.375 sec off, and 0.25 sec on, 0.25 sec off.

For both particle sizes and for three of the pulsing conditions considered, the 8-in. bed height offers the best heat-transfer rate. A possible explanation, somewhat consistent with visual observation, is that, in the 4-in. bed, resistance to the high pulsed-gas velocity is low and the whole bed is expanded uniformly rather than lifting the dense phase past

the heater. In the 12-in. bed, the higher static pressure at the 3-in. level causes the gas void to disperse slowly into the particulate phase, resulting in low particle population at the heater surface at this level.

308-1945 Rev. 1

Fig. 48. Effect of Static-bed Height on Heat-transfer Coefficients in Fluidized Beds (Particles: 138- μ m glass beads; heater length: 0.5 in.; heater position: 3 in.)

308-1912 Rev. 1

Fig. 49. Effect of Static-bed Height on Heat-transfer Coefficients in Pulsed Beds, with 0.5-sec On-period and 0.5-sec Off-period (Particles: 138- μ m glass beads; heater length: 0.5 in.; heater position: 3 in.)

Fig. 50. Effect of Static-bed Height on Heat-transfer Coefficients in Pulsed Beds with 0.2-sec On-period and 0.6-sec Off-period (Particles: 138- μ m glass beads; heater length: 0.5 in.; heater position: 3 in.)

308-1913 Rev. 1

Fig. 51. Effect of Static-bed Height on Heat-transfer Coefficients in Pulsed Beds, with 0.125- and 0.25-sec On-periods and 0.375- and 0.25-sec Off-periods (Particles: 580- μ m glass beads; heater length: 0.5 in.; heater position: 3 in.)

4. Effect of Heater Length

The dependency of heat-transfer rate on heater length in pulsed and fluidized beds was investigated using heaters of 0.5-, 2-, and 4 in. length

308-1911 Rev. 1

Fig. 52. Effect of Heater Length on Heat-transfer Coefficients for 580- μ m Glass Beads (Heater position: 3 in.)

for both 138- and 580- μ m glass beads. Figures 52 and 53 show the effect of heater length in which the ratio of the heat-transfer coefficients h_L of the 2- and 4-in. heaters to those $h_{0.5}$ of the 0.5-in. heater, chosen as a standard, is plotted against the dimensionless gas velocity (v_0/v_{mb}) for 580- and 138- μ m glass-bead-air systems, respectively. Figure 52 shows that heat-transfer rates decrease more rapidly with heater length in pulsed beds than in fluidized beds. This result bears out an observation from the motion pictures that there is less radial particle motion around an internal surface in pulsed beds than in fluidized beds. Although Fig. 53 also shows the same effect of the heater length at the lower velocities for the 138- μ m particles, at higher gas velocities the heat-transfer ratio is roughly the same for pulsed conditions and fluidized operation. This indicates that the pulsed bed approaches the fluidized-bed state at higher gas velocities for the smaller particles. In both figures, two solid reference lines are drawn on the assumption that the heat-transfer coefficient is inversely proportional to the square root of heater length.

308-1917 Rev. 1

Fig. 53. Effect of Heater Length on Heat-transfer Coefficients for 138- μ m Glass Beads (Heater position: 3 in.)

Gel'perin *et al.*³⁶ have reported no effect of heater length on heat-transfer rate. In their experiment, 4.3- and 8-in. heaters were used. For these heater sizes, their result may be expected, since, in a fluidized bed, the mean traveling lengths of particles on a boundary surface may be shorter than these heater lengths.

To see the degree of a mean traveling length, we took high-speed motion pictures for 580- μm glass beads at $v_0/v_{mb} = 1.45$. The fraction of tracer particles, β , that moves away from the surface was counted. Assuming the particles near the field of view (0.5 in. long) behave as do the particles observed, the mean traveling length, λ , is estimated as

$$\beta = \frac{0.5}{\lambda} \quad (34)$$

From the picture, β was determined as 0.16. Therefore, λ may be 3.1 in. for this condition.

In summary, pulsed beds offer the greatest advantage when used with shorter heaters.

5. Effect of Physical and Thermal Properties of Particles and Gas

a. Effect of Particle Properties. Three different materials (glass beads, aluminum shot, and copper shot) were tested for approximately the same particle size. The results are shown in Figs. 39, 54, and 55. The effect of the particle thermal properties on heat-transfer coefficients in a pulsed bed relative to those in a fluidized bed does not seem to be significantly different for glass beads (Fig. 39) and for aluminum shot (Fig. 54). However, the particle density, which directly relates to the minimum fluidization velocity, has quite an effect on the pattern of heat transfer in a pulsed bed. Pulsed-bed operation is very advantageous for a bed of copper shot, that is, providing a higher maximum heat-transfer rate and a sharp increase in heat-transfer coefficient at low integral gas velocities.

308-1954 Rev. 1

Fig. 54. Heat-transfer Coefficients for an Aluminum-Air System (Average diameter of particle: 291 μm)

Fig. 55. Heat-transfer Coefficients for a Copper-Air System (Average diameter of particle: 313 μm)

the characteristics of a solid particle-gas system (see Fig. 56), the effect of thermal properties of solid particles in a pulsed bed may be assumed to

308-1946 Rev. 1

Fig. 56. Effect of Solid Thermal Properties on Heat-transfer Coefficients

ties on the heat-transfer rate. Figure 57 compares bed stroke for these three gases with pulsing conditions of 0.2 sec on, 0.6 sec off, and 0.2 sec on, 0.4 sec off. These values of bed stroke were obtained from motion pictures. Gas properties do not seem to cause a significant difference in bed stroke. Bed stroke is affected by volume flowrate rather than by viscosity for this small particle size, although for larger particles, gas viscosity may have a dominant effect. However, with a gas of lower viscosity, the bed has a shorter settling time, due to the lower resistance. This effect is shown in Fig. 58 for carbon dioxide and air.

Heat-transfer coefficients for beds with various gases are shown in Figs. 59-61 for air, carbon dioxide, and helium, respectively. The improvement in heat-transfer rate obtained with pulsed-bed operation over fluidized-bed operation at relatively low gas velocity is greater for carbon dioxide than for air. This phenomenon is explained by the fact that, although both gases use the same bed stroke, the faster settling time for carbon dioxide results in a lower average void fraction of the bed. Also, a pulsed bed seems to offer a greater heat-transfer advantage for the gas of higher conductivity. According to the proposed heat-transfer model, the increment of heat-transfer coefficient for shortening the residence time is larger for the higher gas conductivity than for the lower conductivity. This tendency agrees with the experimental results. The maximum heat-transfer rate in a pulsed bed was observed to be 28% higher than that in a fluidized bed. Table VI lists the maximum heat-transfer rates.

be the same as in a fluidized bed. In a fluidized bed, the heat-transfer coefficient increases with solid heat capacity and is independent of solid thermal conductivity. This is evident from the comparison of the proposed heat-transfer mechanism with the experimental data with glass beads and aluminum shot. This is also supported by Ziegler *et al.*²¹

b. Effect of Gas Properties.

Helium and carbon dioxide were used in addition to air for 138- μ m glass beads to see the effect of gas proper-

Fig. 57. Bed Stroke vs Pulsed-gas Velocity for Various Gases

Fig. 58. Pulsed-bed Movement with Carbon Dioxide and Air

308-1940 Rev. 1

Fig. 59. Heat-transfer Coefficients for Fluidized and Pulsed Beds with Air (138- μ m glass beads)

Fig. 60. Heat-transfer Coefficients for Fluidized and Pulsed Beds with Carbon Dioxide (138- μ m glass beads)

Fig. 61. Heat-transfer Coefficients for Fluidized and Pulsed Beds with Helium (138- μ m glass beads)

TABLE VI. Maximum Heat-transfer Coefficients and Nusselt Numbers for Various Gases

	Air		Carbon Dioxide		Helium	
	h	Nu	h	Nu	h	Nu
Fluidized bed	164	8.96	136	13.4	290	2.91
Pulsed bed:						
0.2 sec on, 0.6 sec off	160	8.74	137	13.5	290	2.91
0.2 sec on, 0.4 sec off	158	8.64	125	12.3	327	3.27

6. Estimation of Heat-transfer Coefficients in Pulsed Beds

Proposed models are used with $\eta = 0.015$, which is the same as for a fluidized bed, to estimate the heat-transfer coefficients in pulsed beds.

The relationship between particle residence time and gas throughput has not yet been established in a fluidized-bed system because of the complexity of the bubble behavior. Several works,^{36,37} however, have treated the particle motion on a wall related to a rising gas bubble near the wall. In a pulsed-bed system that has good pulsing characteristics, it may be possible to estimate the particle residence time from the simple behavior of a pulsed bed.

Two kinds of pulsed-bed behavior are considered here. The first is one in which there is no excess gas voidage at the heater surface, and the dense solid phase moves up and down over the heater surface. Motion pictures taken at various positions along an internal surface (heater surface) showed this behavior characteristic to be present in the upper part of the bed for the large particle sizes. The second behavior is that of large gas slugs passing the heater surface and turning over the particles at the heater surface during each pulse cycle.

For either of these cases, the motion of particles at the heater surface is related to the total bed movement during each cycle. This total bed movement is well represented by Eq. 23. With these values of bed stroke, two kinds of bed behavior are considered as follows:

a. Dense-phase Region. The residence time of particles on a heater surface of length ℓ is expressed as

$$\begin{aligned}\tau &= (t_{\text{on}} + t_{\text{off}}) \frac{\ell}{\ell + aS_b} b[1 + 2(1-b) + 3(1-b)^2 + 4(1-b)^3 + \dots] \\ &= (t_{\text{on}} + t_{\text{off}}) \frac{\ell}{\ell + aS_b} \frac{1}{b},\end{aligned}\tag{35}$$

where

t_{off} = off-period,

ℓ = heater length,

a = lag factor due to friction between the particles and the wall,

b = mixing factor for a pulsed bed (fraction of particles that do not again contact the heater surface in subsequent pulse periods),

and

S_b = bed stroke (see Eq. 23).

The first part of Eq. 35 is explained as follows: During a complete pulse cycle $(t_{\text{on}} + t_{\text{off}})$, a heater of length l is contacted by a longitudinal portion of bed equal to $l + aS_b$. Therefore, the average particle-residence time for one cycle of pulsation is

$$\tau_0 = (t_{\text{on}} + t_{\text{off}}) \frac{l}{l + aS_b} \quad (36)$$

To determine the lag factor, a , we photographed the particle motion at the internal surface and at the top surface of the bed with a high-speed cine-camera. From the pictures of the internal surface, the average particle-residence time for one cycle was calculated with Eq. 16 from the instantaneous particle-residence time. Figure 62 shows the instantaneous residence time calculated with Eq. 13 for 580- μm glass beads with a pulsing condition of 0.125 sec on, 0.375 sec off, as an example.

Fig. 62. Instantaneous Particle-residence Time in a Pulsed Bed

From these average particle-residence times for five different pulsing conditions, the lag factor, a , was determined to be 0.8. Table VII compares the average particle-residence times from Eqs. 16 and 36 using 0.8 as the lag factor for a 0.5-in. heater. For this kind of bed movement, there is relatively little radial particle motion. Hence, some particles that have left the heater surface once may return

to the heater surface at the completion of a pulsing cycle at a higher temperature than that of the bulk bed. To account for this effect, the last part of Eq. 35 involving the mixing factor was introduced. The mixing factor, b , has to be determined empirically. From the characteristics of pulsed-bed behavior, it seems reasonable to assume that b is proportional to S_b/l . Therefore, Eq. 35 is rewritten as

$$\tau = (t_{\text{on}} + t_{\text{off}}) \frac{l}{l + aS_b} \frac{l}{cS_b} \quad (37)$$

The factor c was taken to be 0.1 for 580- μm glass beads on the basis of motion-picture analysis and heat-transfer measurement. For 138- μm glass beads, heat-transfer results determined the value of c to be 1.0.

TABLE VII. Average Residence Time of Particles for One Cycle of Pulsation

On-period, sec	Off-period, sec	v_0 , ft/sec	τ_0 from Eq. 16, sec	τ_0 from Eq. 36, sec
0.125	0.375	0.406	0.182	0.184
0.125	0.375	0.504	0.129	0.136
0.125	0.375	0.826	0.072	0.074
0.25	0.25	0.56	0.259	0.243
0.25	0.25	1.015	0.078	0.078

b. Slugging Region. For smaller particle sizes, a slugging type of bed behavior sometimes occurs. If we assume complete slugging behavior, the discontinuity of particle motion on the heater surface due to the presence of gas slugs has to be considered. At the beginning of a pulse cycle, particles move up on the heater surface. Then the gas slug turns over the particles as it goes by the heater, and the particles move down. The final step of the particle motion cycle is that of particles at rest on the heater surface. The residence time of particles for each period is expressed as

$$\tau_{up} = t_{on} \frac{\ell}{\ell + S_b}, \quad (38)$$

$$\tau_{down} = (t_{off} - t_r) \frac{\ell}{\ell + S_b}, \quad (39)$$

and

$$\tau_r = t_r + \tau_{up} + \tau_{down}, \quad (40)$$

where

τ_{up} = particle residence time during upward motion,

τ_{down} = particle residence time during downward motion,

τ_r = particle residence time for resting particles,

and

t_r = period while bed surface does not move.

Heat transfer may consist of these three portions as

$$h_t = h(\tau_{up})k_1 + h(\tau_{down})k_2 + h(\tau_r)k_3, \quad (41)$$

where k_1 , k_2 , and k_3 are the time fractions during each pulse cycle expressed as

$$k_1 = \left(1 - \frac{\ell}{2S_b}\right) \frac{t_{on}}{t_{on} + t_{off}}, \quad (42)$$

$$k_2 = \left(1 - \frac{\ell}{2S_b}\right) \frac{t_{off} - t_r}{t_{on} + t_{off}}, \quad (43)$$

and

$$k_3 = 1 - k_1 - k_2. \quad (44)$$

Furthermore, the average voidage during one cycle of pulsation has to be considered:

$$h = h(\tau_1, \tau_2, \tau_3, k_1, k_2, k_3) \frac{1 - \epsilon}{1 - \epsilon_0}. \quad (45)$$

An actual pulsed bed of smaller particles may exist between these two cases, one for the dense phase and one for the slugging region.

The results of these calculations are compared with experimental data for several pulsing conditions and three heater lengths in Figs. 63-65 for a 580- μm glass-bead-air system and in Figs. 66 and 67 for a 138- μm glass-bead-air system. For 580- μm glass beads, on the basis of photographic observation, only the dense-phase region was applicable for this size of particles. In Figs. 66 and 67 for 138- μm glass beads, two lines corresponding to Eqs. 36 and 45 are drawn.

By the method discussed in this section, for a certain range of pulsing conditions, heat-transfer coefficients may be estimated if a pulsing condition is known.

308-1908 Rev. 1

Fig. 63. Data Comparison with Predictions for 580- μm Glass Beads with 0.125-sec On-period and 0.375-sec Off-period

308-1914 Rev. 1

Fig. 64. Data Comparison with Predictions for 580- μm Glass Beads with 0.25-sec On-period and 0.25-sec Off-period

308-1943 Rev. 1

Fig. 65. Data Comparison with Predictions for 580- μ m Glass Beads with 0.25-sec On-period and 0.5-sec Off-period

308-1916 Rev. 1

Fig. 66. Data Comparison with Predictions for 138- μ m Glass Beads with 0.2-sec On-period and 0.6-sec Off-period

Fig. 67

Data Comparison with Predictions for 138- μ m Glass Beads with 0.2-sec On-period and 0.4-sec Off-period

308-1941 Rev. 1

VI. CONCLUSIONS

The bed behavior and the heat-transfer characteristics (from an internal surface to the bed) in pulsed-bed operation have been studied.

The unique characteristics of pulsed beds have been found to be the following:

1. Pressure-drop patterns are reproducible and regular for each pulse cycle.
2. Maximum pressure drop increases linearly with pulsed-gas velocity.
3. The bed expansion ratios increase with
 - a. Increasing gas velocity.
 - b. Decreasing pulse frequency.
 - c. Decreasing fraction of on-period.
4. Larger or heavier particles have more regular dependence on pulsing conditions.
5. Good particle motion exists below the minimum fluidizing velocity.
6. The stroke of the bed can be estimated.
7. There exists an upper limit of on-period and a lower limit of off-period for fully controlled pulsed-bed behavior.

Pulsed-bed operation provides advantages for the heat-transfer process between a heater and a bed for the following situations:

1. Large particle sizes; in other words, particles that have high minimum fluidization velocity.
2. Short heater.
3. Heaters located in the upper part of a bed.

The relatively simple mathematical model proposed for the heat-transfer mechanism has made it possible to predict the heat-transfer coefficient in a solid-particle-gas system with parameter η .

If particle properties are known, including minimum bubbling velocity, the limits of the on- and off-periods given by Eqs. 21 and 24 give the range of pulsing conditions that provides satisfactory pulsed-bed behavior. After on- and off-periods satisfying the above limitations are chosen, the bed stroke is predicted by Eq. 23. Using the relations between this bed stroke and particle residence time that are described by Eq. 37 and the proposed heat-transfer model allows heat-transfer coefficients in a pulsed bed to be predicted.

VII. SUGGESTIONS FOR FUTURE WORK

Smaller particles have been found to have longer bed settling times, which cause poor pulsed-bed performance. If there is a way to shorten this settling time, pulsed-bed operation will have an added advantage over fluidized-bed operation. A possible solution (shown in Fig. 68) is to feed pulsed gas alternately to two parallel columns that are connected to a common exit. While the bed is settling in Column A, the gas is flowing in Column B. Therefore, if Valve C in the exhaust line is adjusted, back pressure at the exit may help the settling of the bed in the column. Also, since there will be continuous flow in the feed line, this scheme may have the further advantage of eliminating the large surge tank.

Fig. 68
Pulsed-bed Operation in
Two Parallel Columns

Since the investigation has been carried out with one column size, the scale-up problem has not been considered. It would be worthwhile to extend the experiment to different column sizes.

In addition to the points made above, many other aspects of pulsed beds should be studied to fully understand their operation, such as heat transfer between solid particles and gas, and mass transfer between an immersed object and a bed, as well as between solid particles and gas.

APPENDIX A

Maximum Pressure Drops, Average Pressure Drops,
and Bed Expansions

Tables Contained in This Appendix:

<u>No.</u>	<u>Title</u>	<u>Page</u>
A.1.	Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 580- μm Glass Beads with $v_{mf} =$ 0.70 ft/sec and Static Bed Height = 8 in.	70
A.2.	Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 301- μm Glass Beads with $v_{mf} =$ 0.258 ft/sec and Static Bed Height = 8 in.	72
A.3.	Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 138- μm Glass Beads with $v_{mf} =$ 0.068 ft/sec and Static Bed Height = 8 in.	73
A.4.	Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 73- μm Glass Beads with Static Bed Height = 8 in.	75

TABLE A.1. Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 580- μm Glass Beads with $v_{mf} = 0.70$ ft/sec and Static Bed Height = 8 in.

v_0/v_{mf}	v/v_{mf}	t_{on} , sec	t_{off} , sec	ΔP_{max} , psi	$A\Delta P_{max}/W$	Expansion	ΔP_{ave} , psi
0.709	1.275	0.312	0.25	0.482	1.128	1.09	0.228
0.710	1.290	0.50	0.406	0.482	1.128	1.14	0.255
0.828	1.160	0.625	0.25	0.455	1.062	1.09	0.312
0.699	1.345	0.61	0.562	0.482	1.128	1.15	0.248
0.805	1.203	0.75	0.375	0.468	1.092	1.11	0.304
0.890	1.102	0.89	0.218	0.455	1.062	1.20	0.351
0.666	1.310	0.844	0.813	0.498	1.162	1.14	0.231
0.817	1.210	1.16	0.562	0.455	1.062	1.13	0.305
0.961	1.73	0.312	0.25	0.569	1.328	1.23	0.266
0.965	1.86	0.47	0.437	0.569	1.328	1.30	0.267
1.058	1.54	0.625	0.281	0.546	1.277	1.23	0.347
0.956	1.83	0.625	0.561	0.596	1.391	1.27	0.271
1.095	1.66	0.735	0.375	0.575	1.341	1.20	0.322
1.192	1.51	0.875	0.234	0.553	1.290	1.19	0.369
0.905	1.91	0.782	0.875	0.639	1.490	1.25	0.236
1.090	1.67	1.048	0.562	0.597	1.393	1.27	0.320
1.177	1.49	1.28	0.344	0.540	1.260	1.20	0.368
1.072	1.64	1.405	0.75	0.568	1.326	1.23	0.309
1.188	1.47	1.311	0.814	0.555	1.295	1.20	0.366
1.240	2.40	0.281	0.381	0.682	1.591	1.39	0.269
1.222	2.36	0.437	0.406	0.682	1.591	1.40	0.262
1.450	2.02	0.640	0.25	0.695	1.621	1.32	0.351
1.238	2.33	0.640	0.562	0.711	1.660	1.42	0.266
1.420	2.16	0.718	0.375	0.739	1.725	1.36	0.324
1.568	1.89	0.906	0.187	0.67	1.564	1.32	0.387
1.193	2.22	0.875	0.75	0.695	1.622	1.45	0.249
1.408	2.13	1.03	0.531	0.638	1.490	1.40	0.317
1.412	2.03	1.22	0.375	0.596	1.391	1.32	0.363
1.550	2.20	1.375	0.75	0.668	1.560	1.32	0.307
1.558	1.94	1.655	0.406	0.612	1.430	1.36	0.363
1.82	3.64	0.281	0.281	0.905	2.255	1.85	0.259
2.10	4.06	0.469	0.437	0.938	2.19	2.04	0.258
2.42	3.28	0.828	0.297	0.924	2.16	2.04	0.348
2.00	3.86	0.61	0.561	0.924	2.16	2.04	0.234
2.34	3.57	0.720	0.375	0.880	2.06	2.28	0.309
2.57	3.20	0.875	0.218	0.880	2.06	1.97	0.372
1.94	3.88	0.828	0.828	0.936	2.19	2.22	0.255
2.31	3.40	1.06	0.561	0.852	1.99	2.16	0.326
2.56	3.22	1.28	0.344	0.824	1.92	2.04	0.353
2.31	3.52	1.44	0.75	0.839	1.96	2.10	0.292
2.55	3.27	1.604	0.453	0.808	1.90	1.97	0.363
0.369	0.72	0.312	0.297	0.349	0.816	-	0.177
0.379	0.688	0.500	0.406	0.340	0.795	-	0.179
0.436	0.634	0.625	0.281	0.304	0.711	-	0.204
0.370	0.701	0.625	0.562	0.349	0.816	-	0.175
0.472	0.570	0.906	0.187	0.287	0.671	-	0.224
0.194	0.370	0.625	0.562	0.148	0.346	-	0.077
0.616	1.17	0.312	0.281	0.452	1.055	1.045	0.244
0.618	1.16	0.50	0.437	0.452	1.055	1.045	0.241
0.716	1.04	0.625	0.281	0.439	1.025	1.03	0.297
0.614	1.162	0.625	0.562	0.452	1.055	1.045	0.234
0.705	1.060	0.75	0.375	0.443	1.035	1.03	0.290
0.785	0.972	0.906	0.218	0.430	1.002	1.01	0.344
0.597	1.18	0.844	0.813	0.452	1.055	1.05	0.220
0.701	1.06	1.092	0.562	0.430	1.002	1.03	0.280
0.775	0.992	1.28	0.344	0.430	1.002	-	0.330

TABLE A.1 (Contd.)

v_0/v_{mf}	v/v_{mf}	t_{on} , sec	t_{off} , sec	ΔP_{max} , psi	$A\Delta P_{max}/W$	Expansion	ΔP_{ave} , psi
1.590	3.02	0.312	0.281	0.841	1.970	1.60	0.352
1.62	3.23	0.437	0.437	0.770	1.802	1.60	0.281
1.89	2.64	0.625	0.250	0.716	1.678	1.60	0.342
1.58	3.05	0.595	0.562	0.770	1.800	1.72	0.253
1.83	2.74	0.750	0.375	0.706	1.652	1.60	0.328
1.96	2.45	0.875	0.218	0.712	1.665	1.48	0.327
1.536	3.11	0.812	0.845	0.778	1.82	1.72	0.241
1.805	2.84	1.03	0.594	0.756	1.77	1.66	0.331
1.996	2.49	1.25	0.312	0.756	1.77	1.48	0.379
1.12	2.24	0.25	0.25	0.931	1.45	1.27	0.465 ^a
1.140	2.21	0.437	0.426	0.922	1.436	1.31	0.629 ^a
1.35	2.00	0.594	0.281	0.850	1.322	1.27	0.534 ^a
1.122	2.19	0.594	0.562	0.960	1.49	1.31	0.432 ^a
1.295	1.94	0.750	0.375	0.941	1.46	1.27	0.488 ^a
1.430	1.78	0.906	0.218	0.914	1.42	1.25	0.521 ^a
1.178	2.09	0.970	0.742	0.995	1.54	1.27	0.418 ^a
1.282	1.413	1.06	0.531	0.995	1.54	1.27	0.495 ^a
1.413	1.80	1.250	0.344	0.924	1.43	1.27	0.578 ^a
0.715	2.86	0.125	0.375	1.058	1.648	1.174	0.351 ^a
0.891	3.56	0.125	0.375	1.19	1.85	1.23	0.394 ^a
0.598	2.39	0.125	0.375	0.95	1.48	1.13	0.308 ^a
0.456	1.82	0.125	0.375	0.833	1.295	1.07	0.266 ^a
0.423	0.565	0.375	0.125	0.448	0.697	-	0.344 ^a
0.937	1.250	0.375	0.125	0.690	1.072	1.07	0.531 ^a
1.290	1.72	0.375	0.125	0.869	1.350	1.15	0.611 ^a
1.755	2.34	0.375	0.125	1.04	1.62	1.32	0.640 ^a
1.151	1.535	0.375	0.125	0.824	1.28	1.11	0.574 ^a
0.447	0.895	0.203	0.203	0.581	0.905	-	0.297 ^a
0.75	1.50	0.203	0.203	0.752	1.17	1.07	0.410 ^a
0.985	1.97	0.203	0.203	0.868	1.35	1.13	0.427 ^a
1.27	2.54	0.203	0.203	1.10	1.71	1.19	0.531 ^a
1.45	2.90	0.203	0.203	1.20	1.87	1.34	0.582 ^a
0.303	1.212	0.125	0.375	0.564	1.321	1.11	0.179
0.690	2.76	0.125	0.375	0.680	1.60	1.22	0.204
0.954	3.816	0.125	0.375	0.822	1.93	1.35	0.232
1.202	4.808	0.125	0.375	1.054	2.47	1.48	0.325
0.624	1.872	0.125	0.25	0.545	1.28	1.095	0.223
0.964	2.89	0.125	0.25	0.706	1.66	1.23	0.266
0.816	2.45	0.125	0.25	0.644	1.51	1.17	0.254
1.198	3.59	0.125	0.25	0.850	1.99	1.32	0.318
1.514	4.542	0.125	0.25	1.063	2.50	1.54	0.390
0.860	1.720	0.125	0.125	0.429	1.01	1.08	0.304
1.176	2.35	0.125	0.125	0.715	1.68	1.16	0.365
1.46	2.92	0.125	0.125	0.786	1.84	1.25	0.393
0.273	-	∞	-	-	-	-	0.091
0.346	-	∞	-	-	-	-	0.123
0.412	-	∞	-	-	-	-	0.187
0.553	-	∞	-	-	-	-	0.251
0.745	-	∞	-	-	-	-	0.318
0.907	-	∞	-	-	-	-	0.385
1.02	-	∞	-	-	-	1.06	0.428
1.215	-	∞	-	-	-	1.10	0.428
1.39	-	∞	-	-	-	1.13	0.428
1.81	-	∞	-	-	-	1.25	0.428
2.31	-	∞	-	-	-	1.38	0.428

^aStatic-bed height = 12 in.

TABLE A.2. Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 301- μ m Glass Beads with $v_{mf} = 0.258$ ft/sec and Static Bed Height = 8 in.

v_0/v_{mf}	v/v_{mf}	t_{on} , sec	t_{off} , sec	ΔP_{max} , psi	$A\Delta P_{max}/W$	Expansion	ΔP_{ave} , psi
0.472	0.945	0.125	0.125	0.273	0.67	-	
0.941	1.88	0.125	0.125	0.471	1.16	-	
1.14	2.28	0.125	0.125	0.533	1.31	1.06	
1.60	3.20	0.125	0.125	0.623	1.53	1.09	
2.09	4.19	0.125	0.125	0.681	1.67	1.17	
0.957	2.86	0.125	0.25	0.510	1.25	1.05	
1.22	3.70	0.125	0.25	0.574	1.41	1.08	
1.42	4.27	0.125	0.25	0.660	1.62	1.16	
1.96	5.87	0.125	0.25	0.735	1.81	1.23	
2.33	6.99	0.125	0.25	0.770	1.89	1.31	
0.511	1.53	0.125	0.25	0.448	1.10	-	
0.394	1.58	0.125	0.375	0.448	1.10	-	
0.835	3.34	0.125	0.375	0.546	1.34	1.06	
1.103	4.41	0.125	0.375	0.645	1.59	1.13	
1.40	5.61	0.125	0.375	0.707	1.74	1.19	
1.79	7.30	0.125	0.375	0.825	2.03	1.25	
0.386	1.93	0.125	0.50	0.440	1.08	-	
0.905	4.52	0.125	0.50	0.614	1.51	1.13	
1.23	6.15	0.125	0.50	0.690	1.70	1.19	
1.46	7.32	0.125	0.50	0.789	1.94	1.28	
2.12	11.6	0.125	0.50	0.923	2.27	1.44	
2.46	12.3	0.125	0.50	1.05	2.58	1.56	
0.424	1.27	0.25	0.50	0.412	1.01	-	
0.575	1.72	0.25	0.50	0.448	1.10	1.03	
1.015	3.23	0.25	0.50	0.538	1.32	1.13	
1.43	4.30	0.25	0.50	0.627	1.54	1.25	
1.94	5.82	0.25	0.50	0.740	1.82	1.28	
2.36	7.09	0.25	0.50	0.833	2.05	1.56	
0.569	1.14	0.25	0.25	0.412	1.01	-	
1.054	2.11	0.25	0.25	0.497	1.22	1.06	
1.51	3.02	0.25	0.25	0.600	1.47	1.14	
2.00	4.00	0.25	0.25	0.636	1.56	1.20	
2.42	4.84	0.25	0.25	0.700	1.72	1.25	
0.550	2.20	0.25	0.75	0.466	1.14	1.06	
0.953	3.81	0.25	0.75	0.591	1.45	1.19	
1.282	5.13	0.25	0.75	0.716	1.76	1.38	
1.530	6.12	0.25	0.75	0.770	1.89	1.50	
1.90	7.59	0.25	0.75	0.833	2.05	1.51	
0.875	1.25	0.50	0.25	0.440	1.08	-	
1.24	1.85	0.50	0.25	0.529	1.30	1.06	
1.71	2.56	0.50	0.25	0.502	1.23	1.22	
2.10	3.14	0.50	0.25	0.546	1.34	1.28	
2.79	4.19	0.50	0.25	0.619	1.52	1.38	
1.15	1.72	0.50	0.25	0.456	1.12	1.08	
0.729	1.46	0.50	0.50	0.425	1.04	1.02	
1.10	2.20	0.50	0.50	0.484	1.19	1.16	
1.65	3.30	0.50	0.50	0.537	1.32	1.22	
2.15	4.30	0.50	0.50	0.610	1.50	1.31	
2.82	5.56	0.50	0.50	0.708	1.74	1.50	
0.120	-	∞	-	-	-	-	0.063
0.284	-	∞	-	-	-	-	0.104
0.510	-	∞	-	-	-	-	0.202
0.615	-	∞	-	-	-	-	0.268
0.823	-	∞	-	-	-	-	0.334
0.982	-	∞	-	-	-	-	0.392
1.30	-	∞	-	-	-	1.02	0.394
1.52	-	∞	-	-	-	1.05	0.403
1.87	-	∞	-	-	-	1.08	0.406
2.10	-	∞	-	-	-	1.10	0.405
2.72	-	∞	-	-	-	1.16	0.402
3.98	-	∞	-	-	-	1.22	
4.81	-	∞	-	-	-	1.28	

TABLE A.3. Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 138- μ m Glass Beads with $v_{mf} = 0.068$ ft/sec and Static Bed Height = 8 in.

v_0/v_{mf}	v/v_{mf}	t_{on} , sec	t_{off} , sec	ΔP_{max} , psi	$A\Delta P_{max}/W$	Expansion	ΔP_{ave} , psi
1.24	2.48	0.156	0.156	0.420	1.08	1.07	0.313
1.56	3.12	0.156	0.156	0.416	1.07	1.08	0.352
2.56	5.12	0.156	0.156	0.447	1.15	1.13	0.348
3.54	7.08	0.156	0.156	0.474	1.22	1.16	0.337
0.71	1.42	0.218	0.218	0.300	0.735	1.03	0.179
1.81	3.62	0.218	0.218	0.425	1.09	1.09	0.365
2.72	5.44	0.218	0.218	0.475	1.22	1.17	0.357
3.62	7.24	0.218	0.218	0.510	1.31	1.25	0.362
5.00	10.00	0.218	0.218	0.681	1.75	1.44	0.370
0.421	1.13	0.218	0.375	0.340	0.833	1.05	0.165
1.70	4.67	0.218	0.375	0.456	1.17	1.12	0.312
3.22	8.76	0.218	0.375	0.533	1.37	1.19	0.326
4.46	12.2	0.218	0.375	0.564	1.45	1.31	0.259
6.57	17.9	0.218	0.375	0.702	1.80	1.40	0.281
2.40	6.57	0.218	0.375	0.439	1.13	1.12	0.294
0.785	2.69	0.218	0.531	0.407	1.05	1.02	0.232
1.37	4.69	0.218	0.531	0.411	1.06	1.09	0.239
2.09	7.15	0.218	0.531	0.453	1.16	1.17	0.224
3.18	11.3	0.218	0.531	0.528	1.35	1.25	0.243
4.85	16.6	0.218	0.531	0.622	1.60	1.41	0.193
6.36	21.8	0.218	0.531	0.706	1.81	1.50	0.234
0.485	0.97	0.375	0.375	0.260	0.636	-	0.141
1.80	3.60	0.375	0.375	0.416	1.07	1.09	0.321
3.37	7.74	0.375	0.375	0.465	1.19	1.25	0.317
4.62	9.14	0.375	0.375	0.510	1.31	1.31	0.282
6.91	13.8	0.375	0.375	0.581	1.49	1.38	0.263
8.61	17.2	0.375	0.375	0.693	1.78	1.41	0.292
0.585	1.75	0.375	0.75	0.407	1.05	1.07	0.217
2.34	7.02	0.375	0.75	0.430	1.10	1.22	0.216
3.80	11.4	0.375	0.75	0.520	1.33	1.43	0.206
4.58	13.8	0.375	0.75	0.572	1.49	1.37	0.199
6.45	19.5	0.375	0.75	0.661	1.70	1.69	0.195
0.519	1.30	0.375	0.57	0.304	0.745	1.03	0.139
2.25	5.65	0.375	0.57	0.447	1.15	1.17	0.268
3.02	7.58	0.375	0.57	0.465	1.19	1.25	0.275
4.17	10.5	0.375	0.57	0.520	1.35	1.33	0.295
4.99	12.5	0.375	0.57	0.564	1.45	1.38	0.231
6.63	16.7	0.375	0.57	0.631	1.62	1.44	0.218
0.920	1.35	0.50	0.25	0.331	0.810	-	0.239
2.11	3.16	0.50	0.25	0.439	1.13	1.12	0.373
3.58	5.35	0.50	0.25	0.501	1.28	1.28	0.376
5.09	7.60	0.50	0.25	0.536	1.39	1.31	0.373
5.81	8.70	0.50	0.25	0.515	1.32	1.38	0.367
7.26	10.9	0.50	0.25	0.595	1.52	1.38	0.346
0.805	1.60	0.50	0.50	0.429	1.10	1.08	0.295
1.75	3.51	0.50	0.50	0.456	1.17	1.19	0.317
3.08	6.17	0.50	0.50	0.465	1.19	1.24	0.307
4.52	9.06	0.50	0.50	0.564	1.45	1.31	0.310
5.65	11.3	0.50	0.50	0.537	1.38	1.38	0.305
7.31	14.6	0.50	0.50	0.537	1.38	1.44	0.282
1.79	3.58	0.22	0.22	0.224	1.09	1.15	a
1.50	3.00	0.22	0.22	0.215	1.05	1.09	a
0.476	0.952	0.22	0.22	0.152	0.741	-	a
2.31	4.62	0.22	0.22	0.267	1.30	1.27	a

TABLE A.3 (Contd.)

v_0/v_{mf}	v/v_{mf}	t_{on}, sec	t_{off}, sec	$\Delta P_{max}, \text{psi}$	$A\Delta P_{max}/W$	Expansion	$\Delta P_{ave}, \text{psi}$
2.07	4.14	0.22	0.22	0.229	1.12	1.21	a
1.75	5.25	0.22	0.44	0.224	1.10	1.27	a
1.42	4.26	0.22	0.44	0.206	1.00	1.15	a
1.87	5.61	0.22	0.44	0.229	1.12	1.24	a
2.19	6.57	0.22	0.44	0.267	1.30	1.33	a
2.32	6.96	0.22	0.44	0.309	1.51	1.37	a
2.09	6.27	0.22	0.44	0.251	1.23	1.27	a
1.84	7.36	0.22	0.66	0.251	1.23	1.33	a
1.62	6.48	0.22	0.66	0.229	1.12	1.27	a
1.21	4.86	0.22	0.66	0.197	0.961	1.18	a
0.76	3.05	0.22	0.66	0.202	0.985	1.06	a
2.18	8.72	0.22	0.66	0.323	1.53	1.52	a
1.96	7.84	0.22	0.66	0.269	1.31	1.39	a
2.25	4.50	0.33	0.33	0.260	1.27	1.27	a
2.15	4.30	0.33	0.33	0.242	1.18	1.24	a
2.00	4.00	0.33	0.33	0.206	1.00	1.23	a
1.60	3.80	0.33	0.33	0.202	0.985	1.15	a
1.41	2.82	0.33	0.33	0.202	0.985	1.09	a
0.852	2.56	0.33	0.66	0.197	0.961	1.11	a
1.67	5.01	0.33	0.66	0.224	1.092	1.27	a
1.91	5.73	0.33	0.66	0.278	1.36	1.30	a
3.04	9.12	0.33	0.66	0.296	1.44	1.33	a
1.22	3.66	0.33	0.66	0.202	0.985	1.18	a
1.33	2.66	0.66	0.66	0.202	0.985	1.15	a
1.69	3.38	0.66	0.66	0.202	0.985	1.21	a
1.88	3.76	0.66	0.66	0.215	1.05	1.27	a
2.10	4.20	0.66	0.66	0.251	1.22	1.33	a
2.22	4.44	0.66	0.66	0.278	1.36	1.39	a
2.31	3.50	0.99	0.66	0.260	1.27	1.33	a
2.19	3.30	0.99	0.66	0.238	1.16	1.27	a
2.09	3.13	0.99	0.66	0.224	1.19	1.24	a
1.88	2.82	0.99	0.66	0.202	0.985	1.21	a
1.59	2.38	0.99	0.66	0.197	0.961	1.12	a
0.14	-	∞	-	-	-	-	0.078
0.28	-	∞	-	-	-	-	0.123
0.51	-	∞	-	-	-	-	0.183
0.68	-	∞	-	-	-	-	0.248
0.84	-	∞	-	-	-	-	0.361
1.14	-	∞	-	-	-	1.05	0.401
1.96	-	∞	-	-	-	1.09	0.409
2.38	-	∞	-	-	-	1.13	0.409
3.08	-	∞	-	-	-	1.16	0.386
3.94	-	∞	-	-	-	1.18	0.388
5.41	-	∞	-	-	-	1.20	0.392

^aStatic-bed height = 4 in.

TABLE A.4. Maximum Pressure Drops, Average Pressure Drops, and Bed Expansions for 73- μ m Glass Beads with Static Bed Height = 8 in.

v_0 , ft/sec	v , ft/sec	t_{on} , sec	t_{off} , sec	ΔP_{max} , psi	$A\Delta P_{max}/W$	Expansion
0.030	0.060	0.25	0.25	0.449	1.11	1.07
0.071	0.142	0.25	0.25	0.403	1.00	1.16
0.015	0.029	0.25	0.25	0.340	0.844	1.05
0.029	0.087	0.25	0.50	0.430	1.07	1.07
0.058	0.173	0.25	0.50	0.407	1.01	1.12
0.092	0.275	0.25	0.50	0.412	1.02	1.13
0.114	0.342	0.25	0.50	0.448	1.11	1.22
0.0130	0.0391	0.25	0.50	0.385	0.955	-
0.0107	0.0427	0.25	0.75	0.394	0.977	1.03
0.0410	0.164	0.25	0.75	0.407	1.01	1.11
0.0754	0.302	0.25	0.75	0.412	1.02	1.14
0.105	0.420	0.25	0.75	0.425	1.05	1.22
0.0962	0.481	0.25	1.00	0.465	1.15	1.31
0.0760	0.380	0.25	1.00	0.412	1.02	1.31
0.0490	0.245	0.25	1.00	0.430	1.07	1.11
0.0236	0.118	0.25	1.00	0.430	1.07	1.09
0.0286	0.0858	0.50	1.00	0.430	1.07	1.09
0.0516	0.155	0.50	1.00	0.430	1.07	1.34
0.0870	0.261	0.50	1.00	0.430	1.07	1.25
0.106	0.318	0.50	1.00	0.479	1.19	1.43
0.0163	0.0589	0.50	1.00	0.430	1.07	1.03
0.0485	0.0970	0.50	0.50	0.412	1.02	1.11
0.0987	0.197	0.50	0.50	0.412	1.02	1.16
0.127	0.254	0.50	0.50	0.456	1.13	1.25
0.0495	0.990	0.50	0.50	0.412	1.02	1.16
0.0311	0.124	0.50	1.50	0.430	1.07	1.12
0.0597	0.239	0.50	1.50	0.430	1.07	1.22
0.0726	0.290	0.50	1.50	0.403	1.00	1.31
0.0960	0.384	0.50	1.50	0.465	1.15	1.49
0.110	0.439	0.50	1.50	0.537	1.33	1.67
0.0372	0.260	0.25	1.50	0.420	1.04	1.10
0.0550	0.385	0.25	1.50	0.430	1.07	1.22
0.0743	0.520	0.25	1.50	0.465	1.15	1.34
0.0870	0.609	0.25	1.50	0.582	1.44	1.43
0.101	0.705	0.25	1.50	0.780	1.94	1.52
0.0434	0.109	1.00	1.50	0.439	1.09	1.18
0.0781	0.195	1.00	1.50	0.492	1.21	1.25
0.0881	0.220	1.00	1.50	0.484	1.19	1.28
0.103	0.257	1.00	1.50	0.403	1.00	1.31
0.118	0.294	1.00	1.50	0.440	1.09	1.34
0.0461	0.0992	1.00	1.00	0.430	1.07	1.18
0.0783	0.157	1.00	1.00	0.412	1.02	1.22
0.105	0.210	1.00	1.00	0.394	0.977	1.25
0.110	0.220	1.00	1.00	0.456	1.13	1.31

APPENDIX B

Instantaneous Residence Time of Particles and Heat-transfer
Coefficients in Fluidized Beds for 301- μ m Glass Beads with
Static Bed Height = 6 in. and Surface Position = 3 in.

Tables Contained in This Appendix:

<u>No.</u>	<u>Title</u>	<u>Page</u>
B.1.	Instantaneous Residence Time of Particles and Heat-transfer Coefficients in Fluidized Beds for $v_0/v_{mb} = 1.10$ and $\bar{\tau} = 0.220$ sec.	77
B.2.	Instantaneous Residence Time of Particles and Heat-transfer Coefficients in Fluidized Beds for $v_0/v_{mb} = 1.38$ and $\bar{\tau} = 0.119$ sec.	79
B.3.	Instantaneous Residence Time of Particles and Heat-transfer Coefficients in Fluidized Beds for $v_0/v_{mb} = 1.51$ and $\bar{\tau} = 0.074$ sec.	83
B.4.	Instantaneous Residence Time of Particles and Heat-transfer Coefficients in Fluidized Beds for $v_0/v_{mb} = 2.06$ and $\bar{\tau} = 0.044$ sec.	87
B.5.	Instantaneous Residence Time of Particles and Heat-transfer Coefficients in Fluidized Beds for $v_0/v_{mb} = 3.24$ and $\bar{\tau} = 0.041$ sec.	91

TABLE B.1. Instantaneous Residence Time of Particles and
Heat-transfer Coefficients in Fluidized Beds
for $v_0/v_{mb} = 1.10$ and $\bar{\tau} = 0.220$ sec

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
0.08	0.520	0.650	83.7
0.10	0.530	0.662	83.0
0.12	0.534	0.668	82.8
0.14	0.540	0.675	82.3
0.16	0.520	0.650	83.7
0.17	0.778	0.972	70.1
0.19	0.760	0.950	70.8
0.21	0.735	0.919	71.9
0.23	0.714	0.892	72.9
0.25	0.696	0.870	73.7
0.27	0.684	0.855	74.2
0.29	0.756	0.944	71.0
0.31	0.730	0.912	72.1
0.33	0.690	0.862	74.0
0.35	0.610	0.762	78.1
0.37	0.490	0.612	85.8
0.39	0.340	0.425	99.1
0.41	0.240	0.300	111.6
0.43	0.150	0.188	126.6
0.45	0.140	0.175	128.6
0.47	0.230	0.287	113.1
0.56	0.416	0.520	91.7
0.58	0.370	0.462	96.1
0.60	0.370	0.462	96.1
0.62	0.396	0.495	93.5
0.64	0.308	0.385	102.7
0.66	0.308	0.385	102.7
0.73	0.292	0.365	104.6
0.75	0.250	0.312	110.2
0.77	0.130	0.162	130.8
0.95	0.124	0.155	132.0
0.97	0.030	0.038	155.4
1.00	0.350	0.438	98.0
1.02	0.430	0.538	90.5
1.04	0.596	0.745	78.9
1.06	0.560	0.700	81.1
1.08	0.865	1.080	66.8

TABLE B.1 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
1.28	0.686	0.858	74.1
1.30	0.664	0.830	75.2
1.32	0.646	0.808	76.1
1.34	0.622	0.778	77.4
1.36	0.590	0.738	79.2
1.51	0.062	0.077	146.7
1.53	0.030	0.038	155.4
1.55	0.280	0.350	106.1
1.57	0.416	0.520	91.7
1.59	0.395	0.494	93.6
1.90	0.075	0.094	143.2
1.92	0.052	0.065	149.3
1.94	0.038	0.047	153.4
1.96	0.030	0.038	155.4
2.04	0.560	0.700	81.1
2.06	0.380	0.475	95.1
2.08	0.330	0.412	100.2
2.10	0.280	0.350	106.1
2.12	0.210	0.262	116.2
2.14	0.160	0.200	124.8
2.16	0.140	0.175	128.8
2.18	0.120	0.150	132.8
2.20	0.086	0.108	140.5
2.30	0.386	0.483	94.4
2.32	0.350	0.438	98.0
2.34	0.330	0.412	100.2
2.36	0.310	0.388	102.4
2.38	0.310	0.388	102.4
2.40	0.290	0.363	104.8
2.42	0.250	0.312	110.2
2.44	0.210	0.263	116.1
2.46	0.186	0.233	120.1
2.48	0.168	0.210	123.3
2.50	0.140	0.175	128.6
2.52	0.120	0.150	132.8
2.54	0.100	0.125	137.2
2.56	0.086	0.108	140.5
2.59	0.160	0.200	124.8
2.61	0.700	0.876	73.5
2.63	0.922	1.152	64.8
2.65	0.900	1.125	65.5
2.67	0.886	1.108	66.0

TABLE B.2. Instantaneous Residence Time of Particles and
Heat-transfer Coefficients in Fluidized Beds
for $v_0/v_{mb} = 1.38$ and $\bar{\tau} = 0.119$ sec

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
0.16	0.208	0.260	116.5
0.18	0.195	0.244	118.6
0.20	0.165	0.206	123.9
0.22	0.115	0.145	133.6
0.24	0.085	0.106	140.8
0.26	0.240	0.300	111.6
0.28	0.225	0.271	115.0
0.30	0.206	0.257	116.8
0.32	0.160	0.200	124.8
0.34	0.150	0.188	126.6
0.36	0.135	0.169	129.7
0.38	0.295	0.369	104.2
0.48	0.220	0.275	114.6
0.50	0.150	0.187	126.7
0.52	0.050	0.062	150.0
0.54	0.034	0.042	154.5
0.56	0.100	0.125	137.2
0.58	0.090	0.112	139.7
0.60	0.070	0.088	144.4
0.62	0.050	0.062	150.0
0.64	0.075	0.094	143.2
0.66	0.115	0.144	133.8
0.68	0.196	0.245	118.4
0.70	0.200	0.250	117.8
0.72	0.206	0.257	116.8
0.74	0.210	0.262	116.2
0.85	0.075	0.094	143.2
0.87	0.072	0.090	144.0
0.89	0.070	0.087	144.6
0.91	0.230	0.287	137.2
0.93	0.200	0.250	117.8
0.95	0.100	0.125	137.2
0.97	0.060	0.075	147.1
1.04	0.106	0.138	134.9
1.06	0.095	0.119	138.4
1.08	0.070	0.087	144.6
1.10	0.035	0.044	154.0
1.12	0.025	0.031	157.1

TABLE B.2 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
1.27	0.080	0.100	142.0
1.29	0.085	0.106	140.8
1.31	0.085	0.106	140.8
1.33	0.090	0.112	139.7
1.35	0.095	0.119	138.4
1.37	0.100	0.125	137.2
1.39	0.120	0.150	138.2
1.41	0.135	0.169	129.6
1.43	0.155	0.194	125.7
1.45	0.135	0.169	129.6
1.47	0.100	0.125	137.2
1.49	0.065	0.081	145.9
1.51	0.040	0.050	152.6
1.55	0.062	0.077	146.7
1.57	0.045	0.056	151.3
1.59	0.037	0.046	153.6
1.61	0.040	0.050	152.6
1.63	0.060	0.075	147.1
1.65	0.150	0.188	126.6
1.67	0.340	0.424	99.2
1.69	0.306	0.387	102.5
1.71	0.270	0.337	107.5
1.73	0.235	0.294	112.3
1.75	0.200	0.250	117.8
1.77	0.185	0.231	120.3
1.95	0.135	0.169	129.6
1.97	0.160	0.200	124.8
1.99	0.170	0.212	123.0
2.01	0.145	0.181	127.7
2.03	0.100	0.125	137.2
2.05	0.065	0.081	145.9
2.07	0.035	0.044	154.0
2.09	0.025	0.030	157.3
2.11	0.040	0.050	152.6
2.13	0.033	0.041	154.7
2.15	0.030	0.038	155.4
2.17	0.050	0.062	150.0
2.19	0.103	0.129	136.5
2.21	0.436	0.545	90.0
2.23	0.415	0.519	91.7
2.25	0.390	0.488	94.1
2.27	0.275	0.344	106.8

TABLE B.2 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
2.29	0.245	0.306	110.9
2.31	0.130	0.162	130.8
2.33	0.080	0.100	142.0
2.39	0.260	0.325	108.8
2.41	0.235	0.294	112.3
2.43	0.225	0.281	113.8
2.45	0.210	0.262	116.2
2.47	0.198	0.247	118.1
2.49	0.200	0.250	117.8
2.51	0.188	0.235	119.7
2.53	0.125	0.156	131.8
2.55	0.090	0.112	139.7
2.74	0.383	0.478	94.8
2.76	0.300	0.375	103.7
2.78	0.190	0.237	119.5
2.80	0.165	0.206	123.9
3.01	0.130	0.163	130.6
3.03	0.115	0.144	133.8
3.05	0.095	0.119	138.4
3.07	0.080	0.100	142.0
3.09	0.080	0.100	142.0
3.11	0.073	0.091	143.8
3.13	0.065	0.081	145.9
3.15	0.050	0.062	150.0
3.17	0.050	0.062	150.0
3.19	0.050	0.062	150.0
3.21	0.070	0.098	143.6
3.23	0.225	0.281	113.8
3.25	0.190	0.237	119.5
3.27	0.150	0.188	126.6
3.29	0.105	0.131	136.1
3.31	0.080	0.100	142.0
3.33	0.045	0.056	151.3
3.38	0.145	0.181	127.7
3.40	0.125	0.144	133.8
3.42	0.155	0.194	125.7
3.44	0.130	0.163	130.6
3.46	0.100	0.125	137.2
3.48	0.075	0.094	143.2
3.50	0.035	0.044	154.0

TABLE B.2 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
3.55	0.050	0.062	150.0
3.57	0.080	0.100	142.0
3.59	0.165	0.206	123.9
3.61	0.175	0.219	122.0
3.63	0.506	0.632	84.7
3.65	0.500	0.624	85.1
3.67	0.400	0.500	93.2
3.69	0.290	0.362	104.9
3.71	0.250	0.312	110.2
3.73	0.175	0.219	122.0
3.75	0.170	0.212	123.0
3.77	0.103	0.129	122.0
3.79	0.035	0.044	154.0
3.82	0.175	0.219	122.0
3.84	0.175	0.219	122.0
3.86	0.155	0.194	125.7
3.88	0.145	0.181	127.7
3.90	0.125	0.156	131.8
3.92	0.105	0.131	136.1
3.94	0.090	0.112	139.7

TABLE B.3. Instantaneous Residence Time of Particles and
Heat-transfer Coefficients in Fluidized Beds
for $v_0/v_{mb} = 1.51$ and $\bar{\tau} = 0.074$ sec

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
0.01	0.130	0.162	130.8
0.03	0.125	0.156	131.8
0.05	0.125	0.156	131.8
0.07	0.175	0.219	122.0
0.09	0.210	0.262	116.2
0.11	0.175	0.219	122.0
0.13	0.140	0.175	128.6
0.15	0.112	0.140	134.5
0.17	0.085	0.106	140.8
0.19	0.040	0.050	152.6
0.21	0.025	0.030	157.3
0.24	0.070	0.088	144.4
0.26	0.062	0.077	146.7
0.28	0.060	0.075	147.1
0.30	0.073	0.091	143.8
0.32	0.088	0.110	140.1
0.34	0.093	0.116	138.9
0.36	0.100	0.125	137.2
0.38	0.100	0.125	137.2
0.40	0.085	0.106	140.8
0.42	0.072	0.090	144.0
0.44	0.065	0.081	145.9
0.46	0.068	0.085	145.0
0.48	0.048	0.060	150.4
0.50	0.041	0.051	152.4
0.52	0.045	0.056	151.3
0.54	0.158	0.198	125.1
0.56	0.100	0.125	137.2
0.58	0.065	0.081	145.9
0.60	0.030	0.038	155.4
0.63	0.106	0.133	135.8
0.65	0.100	0.125	137.2
0.67	0.150	0.188	126.6
0.69	0.115	0.144	133.8
0.71	0.085	0.106	140.8
0.73	0.055	0.069	148.4
0.75	0.040	0.050	152.6
0.77	0.070	0.088	144.4
0.79	0.055	0.069	148.4
0.81	0.040	0.050	152.6
0.83	0.030	0.038	155.4

TABLE B.3 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
0.85	0.030	0.038	155.4
0.87	0.050	0.062	150.0
0.89	0.200	0.250	117.8
0.91	0.255	0.319	109.4
1.09	0.055	0.069	148.4
1.11	0.045	0.056	151.3
1.13	0.045	0.056	151.3
1.15	0.040	0.050	152.6
1.17	0.060	0.075	147.1
1.19	0.075	0.094	143.2
1.21	0.053	0.066	149.1
1.23	0.053	0.066	149.1
1.25	0.048	0.060	150.4
1.27	0.050	0.062	150.0
1.29	0.055	0.069	148.4
1.31	0.060	0.075	147.1
1.33	0.065	0.081	145.9
1.35	0.065	0.081	145.9
1.37	0.065	0.081	145.9
1.53	0.225	0.281	113.8
1.55	0.175	0.219	122.0
1.57	0.135	0.169	129.6
1.59	0.100	0.125	137.2
1.61	0.060	0.075	147.1
1.63	0.030	0.038	155.4
1.65	0.100	0.125	137.2
1.67	0.114	0.143	134.0
1.69	0.140	0.175	128.6
1.71	0.220	0.275	114.6
1.73	0.220	0.275	114.6
1.75	0.165	0.206	123.9
1.77	0.175	0.219	122.0
1.79	0.145	0.181	127.7
1.81	0.115	0.144	133.8
1.83	0.100	0.125	137.2
1.85	0.055	0.069	148.4
1.87	0.050	0.062	150.0
1.89	0.075	0.094	143.2
1.91	0.055	0.069	148.4
1.93	0.042	0.052	152.2
1.95	0.042	0.052	152.2
1.97	0.037	0.046	153.6

TABLE B.3 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
2.14	0.038	0.047	153.3
2.16	0.055	0.069	148.4
2.18	0.055	0.069	148.4
2.20	0.044	0.055	151.5
2.22	0.050	0.062	150.0
2.24	0.070	0.088	144.4
2.26	0.150	0.187	126.7
2.28	0.150	0.187	126.7
2.34	0.045	0.056	151.3
2.36	0.030	0.038	155.4
2.38	0.064	0.080	146.1
2.40	0.065	0.081	145.9
2.42	0.075	0.094	143.2
2.44	0.082	0.103	141.4
2.46	0.090	0.112	139.7
2.48	0.100	0.125	137.2
2.50	0.145	0.181	127.7
2.52	0.100	0.125	137.2
2.54	0.075	0.094	143.2
2.56	0.060	0.075	147.1
2.61	0.045	0.056	151.3
2.63	0.035	0.044	154.0
2.65	0.050	0.062	150.0
2.67	0.055	0.069	148.4
2.69	0.042	0.052	152.2
2.71	0.040	0.050	152.6
2.73	0.040	0.050	152.6
2.75	0.050	0.062	150.0
2.78	0.018	0.023	159.0
2.80	0.055	0.069	148.4
2.82	0.200	0.250	117.8
2.84	0.225	0.281	113.8
2.86	0.210	0.262	116.2
2.88	0.190	0.237	119.5
2.90	0.175	0.219	122.0
2.92	0.162	0.202	124.5
2.94	0.145	0.181	127.7
2.96	0.130	0.162	130.8
2.98	0.110	0.138	134.9
3.00	0.090	0.112	139.7
3.02	0.075	0.094	143.2

TABLE B.3 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
3.04	0.070	0.088	144.4
3.06	0.065	0.081	145.9
3.08	0.062	0.077	146.7
3.10	0.060	0.075	147.1
3.27	0.025	0.031	156.1
3.29	0.020	0.025	158.5
3.31	0.025	0.031	156.1
3.33	0.055	0.069	148.4
3.35	0.095	0.118	138.6
3.37	0.110	0.138	134.9
3.39	0.160	0.200	124.8
3.41	0.155	0.194	125.7
3.43	0.140	0.175	128.6
3.45	0.125	0.156	131.8
3.47	0.115	0.144	133.8
3.53	0.050	0.062	150.0
3.55	0.038	0.047	153.3
3.57	0.025	0.031	157.1
3.59	0.023	0.029	157.5
3.70	0.020	0.025	158.5
3.81	0.020	0.025	158.5
3.83	0.020	0.025	158.5
3.85	0.025	0.031	157.1
3.87	0.042	0.052	152.2
3.89	0.060	0.075	147.1
3.91	0.070	0.088	144.4

TABLE B.4. Instantaneous Residence Time of Particles and
Heat-transfer Coefficients in Fluidized Beds
for $v_0/v_{mb} = 2.06$ and $\bar{\tau} = 0.044$ sec

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
0.06	0.142	0.178	128.2
0.08	0.130	0.162	130.8
0.10	0.112	0.140	134.5
0.12	0.090	0.112	139.7
0.14	0.098	0.123	137.6
0.16	0.120	0.150	132.8
0.18	0.090	0.112	139.7
0.20	0.050	0.062	150.0
0.22	0.028	0.035	156.1
0.25	0.042	0.052	154.5
0.27	0.031	0.039	155.2
0.29	0.022	0.028	157.8
0.31	0.020	0.025	158.5
0.33	0.016	0.020	159.8
0.35	0.015	0.019	160.0
0.37	0.010	0.013	161.5
0.39	0.010	0.013	161.5
0.41	0.030	0.038	155.4
0.43	0.054	0.068	148.6
0.45	0.024	0.030	157.3
0.47	0.032	0.040	155.0
0.49	0.032	0.040	155.0
0.51	0.032	0.040	155.0
0.62	0.030	0.038	155.4
0.64	0.030	0.038	155.4
0.66	0.030	0.038	155.4
0.68	0.035	0.044	154.0
0.70	0.038	0.047	153.3
0.72	0.032	0.040	155.0
0.74	0.030	0.038	155.4
0.88	0.020	0.025	158.5
0.90	0.016	0.020	159.8
0.92	0.016	0.020	159.8
0.94	0.020	0.025	158.5
0.96	0.026	0.032	156.9
0.98	0.020	0.025	158.5
1.07	0.100	0.125	137.2
1.09	0.096	0.120	138.2

TABLE B.4 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
1.11	0.082	0.103	141.4
1.13	0.070	0.088	144.4
1.15	0.063	0.079	146.3
1.17	0.050	0.062	150.0
1.19	0.050	0.062	150.0
1.21	0.043	0.054	151.7
1.23	0.049	0.061	150.2
1.25	0.075	0.094	143.2
1.27	0.093	0.116	138.9
1.29	0.050	0.062	150.0
1.31	0.022	0.028	157.8
1.33	0.027	0.034	156.4
1.36	0.030	0.038	155.4
1.38	0.030	0.038	155.4
1.40	0.023	0.029	157.5
1.42	0.018	0.023	159.0
1.44	0.018	0.023	159.0
1.46	0.016	0.020	159.8
1.48	0.023	0.029	157.5
1.50	0.019	0.024	158.8
1.52	0.038	0.047	153.3
1.54	0.028	0.035	156.1
1.56	0.023	0.029	157.5
1.58	0.045	0.056	151.3
1.60	0.108	0.135	135.4
1.62	0.104	0.130	136.3
1.64	0.110	0.138	134.9
1.66	0.121	0.151	132.6
1.68	0.112	0.140	134.5
1.70	0.096	0.120	138.2
1.72	0.086	0.108	140.5
1.74	0.078	0.097	142.6
1.76	0.064	0.080	146.1
1.78	0.044	0.055	151.5
1.80	0.036	0.045	153.8
1.82	0.031	0.039	155.2
1.84	0.031	0.039	155.2
1.86	0.030	0.038	155.4
1.96	0.030	0.038	155.4
1.98	0.022	0.028	157.8
2.00	0.030	0.038	155.4

TABLE B.4 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
2.02	0.064	0.080	146.1
2.04	0.062	0.077	146.7
2.17	0.062	0.077	146.7
2.19	0.078	0.097	142.6
2.21	0.057	0.071	148.0
2.23	0.054	0.068	148.6
2.25	0.060	0.075	147.1
2.27	0.090	0.112	139.7
2.29	0.090	0.112	139.7
2.31	0.050	0.062	150.0
2.33	0.024	0.030	157.3
2.37	0.039	0.049	152.8
2.39	0.028	0.035	156.1
2.41	0.020	0.025	158.5
2.43	0.017	0.021	159.5
2.45	0.018	0.023	159.0
2.47	0.016	0.020	159.8
2.49	0.024	0.030	157.3
2.51	0.032	0.040	155.0
2.53	0.070	0.088	144.4
2.55	0.036	0.045	153.8
2.57	0.050	0.062	150.0
2.59	0.033	0.041	154.7
2.61	0.032	0.040	155.0
2.68	0.068	0.085	145.0
2.70	0.071	0.089	144.2
2.72	0.067	0.084	145.3
2.74	0.060	0.075	147.1
2.76	0.066	0.070	148.2
2.78	0.059	0.074	147.4
2.80	0.065	0.069	148.4
2.82	0.100	0.125	137.2
2.84	0.060	0.075	147.1
2.86	0.030	0.038	155.4
2.90	0.046	0.057	151.4
2.92	0.034	0.042	154.5
2.94	0.026	0.032	156.9
2.96	0.020	0.025	158.5
2.98	0.016	0.020	159.8
3.00	0.016	0.020	159.8

TABLE B.4 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
3.02	0.015	0.018	160.3
3.04	0.018	0.023	159.0
3.06	0.021	0.026	158.3
3.08	0.022	0.027	158.0
3.10	0.040	0.050	152.6
3.12	0.054	0.067	148.8
3.14	0.180	0.225	121.1
3.16	0.158	0.197	125.2
3.18	0.120	0.150	132.8
3.20	0.094	0.118	138.6
3.26	0.090	0.112	139.7
3.28	0.072	0.090	144.0
3.30	0.063	0.079	146.3
3.32	0.056	0.070	148.2
3.34	0.064	0.080	146.1
3.36	0.060	0.075	147.1
3.38	0.052	0.065	149.3
3.40	0.038	0.047	153.3

TABLE B.5: Instantaneous Residence Time of Particles and
Heat-transfer Coefficients in Fluidized Beds
for $v_0/v_{mb} = 3.24$ and $\bar{\tau} = 0.041$ sec

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
0.16	0.073	0.091	143.8
0.18	0.062	0.078	146.5
0.20	0.048	0.060	150.4
0.22	0.038	0.047	153.3
0.24	0.031	0.039	155.2
0.26	0.029	0.036	155.9
0.28	0.026	0.033	156.6
0.30	0.027	0.039	155.2
0.32	0.033	0.041	154.7
0.50	0.055	0.069	148.4
0.52	0.080	0.100	142.0
0.54	0.124	0.155	131.9
0.56	0.100	0.125	137.2
0.61	0.106	0.133	135.8
0.63	0.116	0.146	133.5
0.65	0.116	0.146	133.5
0.69	0.068	0.085	145.0
0.71	0.050	0.062	150.0
0.73	0.040	0.050	152.6
0.75	0.032	0.040	155.0
0.77	0.028	0.035	156.1
0.79	0.029	0.036	155.9
0.81	0.080	0.100	142.0
0.83	0.060	0.075	147.1
0.85	0.040	0.050	152.6
0.87	0.042	0.053	151.9
0.89	0.032	0.040	155.0
0.91	0.024	0.030	157.3
0.93	0.020	0.025	158.5
0.95	0.016	0.020	159.8
0.97	0.013	0.016	160.8
0.99	0.011	0.014	161.3
1.01	0.011	0.014	161.3
1.03	0.010	0.013	161.5
1.05	0.010	0.013	161.5
1.07	0.011	0.014	161.3
1.09	0.011	0.014	161.3
1.11	0.010	0.013	161.5
1.13	0.150	0.088	126.6
1.15	0.100	0.100	142.0
1.17	0.064	0.080	146.1

TABLE B.5 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
1.21	0.055	0.068	148.6
1.23	0.046	0.058	150.8
1.25	0.034	0.042	154.5
1.27	0.030	0.037	155.6
1.29	0.029	0.036	155.9
1.31	0.029	0.036	155.9
1.33	0.050	0.063	149.7
1.35	0.048	0.060	150.4
1.57	0.055	0.068	148.6
1.59	0.034	0.043	154.2
1.61	0.034	0.043	154.2
1.63	0.043	0.054	151.7
1.64	0.146	0.182	127.5
1.66	0.120	0.150	132.8
1.68	0.080	0.100	142.0
1.73	0.059	0.074	147.4
1.75	0.046	0.057	151.0
1.77	0.036	0.045	153.8
1.79	0.030	0.038	155.4
1.81	0.025	0.031	157.1
1.83	0.024	0.030	157.3
1.85	0.025	0.031	157.1
1.87	0.049	0.061	150.2
2.04	0.013	0.016	160.8
2.06	0.017	0.021	159.5
2.08	0.014	0.018	160.3
2.10	0.020	0.025	158.5
2.12	0.150	0.188	126.6
2.14	0.110	0.137	135.1
2.16	0.060	0.075	147.2
2.18 ^a	0.036	0.045	153.8
2.18 ^b	0.117	0.146	133.5
2.20	0.110	0.138	134.9
2.22	0.090	0.112	139.7
2.24	0.070	0.088	144.4
2.26	0.050	0.063	149.7
2.28	0.040	0.050	152.6
2.30	0.035	0.044	154.0
2.32	0.030	0.038	155.4
2.34	0.026	0.033	156.6
2.36	0.048	0.060	150.4
2.38	0.080	0.100	142.0
2.40	0.068	0.085	145.0

TABLE B.5 (Contd.)

Time, sec	τ (0.4 in.), sec	τ (0.5 in.), sec	h , Btu/(hr)(°F)(ft ²)
2.43	0.040	0.050	152.6
2.45	0.026	0.033	156.6
2.47	0.020	0.025	158.5
2.49	0.016	0.020	159.8
2.51	0.016	0.020	159.8
2.53	0.012	0.015	161.0
2.60	0.028	0.035	156.1
2.62	0.022	0.028	157.8
2.64	0.030	0.038	155.4
2.66	0.166	0.208	123.6
2.68	0.130	0.162	130.8
2.70	0.100	0.125	137.2
2.72	0.060	0.075	147.1
2.74	0.057	0.071	148.0
2.76	0.060	0.075	147.1
2.78	0.058	0.073	147.6
2.80	0.046	0.058	150.8
2.82	0.035	0.044	154.0
2.84	0.028	0.035	156.1
2.86	0.025	0.031	157.1
2.88	0.024	0.030	157.3
2.90	0.034	0.043	154.2
2.92	0.042	0.053	151.9
3.12	0.108	0.135	135.4
3.14	0.110	0.138	134.9
3.16	0.088	0.110	140.1
3.18	0.090	0.112	139.7
3.20	0.124	0.155	131.9
3.22	0.080	0.100	142.0
3.24	0.080	0.100	142.0
3.26	0.050	0.062	150.0
3.28	0.060	0.075	146.9
3.30	0.050	0.062	150.0
3.32	0.044	0.055	151.5
3.34	0.031	0.039	155.2
3.36	0.027	0.034	156.4
3.38	0.029	0.036	155.9
3.40	0.025	0.030	157.3
3.42	0.017	0.021	159.5

^aParticles going out.^bParticles coming in.

APPENDIX C

Bed Movements

Tables Contained in This Appendix:

<u>No.</u>	<u>Title</u>	<u>Page</u>
C.1.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.404$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 4 in.	100
C.2.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.558$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 4 in.	100
C.3.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.704$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 4 in.	101
C.4.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.859$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 4 in.	102
C.5.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.548$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 4 in.	103
C.6.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.731$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 4 in.	103
C.7.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.837$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 4 in.	104
C.8.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.992$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 4 in.	105
C.9.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.406$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 8 in.	106
C.10.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.504$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 8 in.	106

<u>No.</u>	<u>Title</u>	<u>Page</u>
C.11.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.588$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 8 in.	107
C.12.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.714$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 8 in.	108
C.13.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.834$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 8 in.	109
C.14.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.549$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 8 in.	110
C.15.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.767$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 8 in.	110
C.16.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.856$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 8 in.	111
C.17.	Bed Movement for 580- μ m Glass Beads with $v_0 = 1.05$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 8 in.	111
C.18.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.318$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 8 in.	112
C.19.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.434$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.75$ sec, and Static-bed Height = 8 in.	112
C.20.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.536$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.75$ sec, and Static-bed Height = 8 in.	113
C.21.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.588$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.75$ sec, and Static-bed Height = 8 in.	114

<u>No.</u>	<u>Title</u>	<u>Page</u>
C.22.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.514$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 12 in.	115
C.23.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.638$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 12 in.	115
C.24.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.770$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 12 in.	116
C.25.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.834$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and Static-bed Height = 12 in.	116
C.26.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.500$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 12 in.	117
C.27.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.798$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 12 in.	117
C.28.	Bed Movement for 580- μ m Glass Beads with $v_0 = 0.907$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 12 in.	118
C.29.	Bed Movement for 580- μ m Glass Beads with $v_0 = 1.162$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and Static-bed Height = 12 in.	119
C.30.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.0786$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 4 in.	120
C.31.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.118$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 4 in.	120
C.32.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.180$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 4 in.	121

<u>No.</u>	<u>Title</u>	<u>Page</u>
C.33.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.319$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 4 in.	121
C.34.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.086$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 4 in.	122
C.35.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.130$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 4 in.	122
C.36.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.280$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 4 in.	123
C.37.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.447$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 4 in.	123
C.38.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.0907$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 4 in.	124
C.39.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.161$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 4 in.	124
C.40.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.290$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 4 in.	125
C.41.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.396$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 4 in.	125
C.42.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.068$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 8 in.	126
C.43.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.163$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 8 in.	126

<u>No.</u>	<u>Title</u>	<u>Page</u>
C.44.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.259$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 8 in.	127
C.45.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.396$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 8 in.	128
C.46.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.118$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 8 in.	129
C.47.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.178$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 8 in.	129
C.48.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.403$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 8 in.	130
C.49.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.050$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 8 in.	130
C.50.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.004$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 8 in.	131
C.51.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.223$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 8 in.	131
C.52.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.330$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 8 in.	132
C.53.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.057$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 12 in.	132
C.54.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.142$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 12 in.	133

<u>No.</u>	<u>Title</u>	<u>Page</u>
C.55.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.273$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 12 in.....	133
C.56.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.421$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and Static-bed Height = 12 in.....	134
C.57.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.098$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 12 in.....	134
C.58.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.208$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 12 in.....	135
C.59.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.334$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and Static-bed Height = 12 in.....	135
C.60.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.90$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 12 in.....	136
C.61.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.200$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 12 in.....	136
C.62.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.272$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 12 in.....	137
C.63.	Bed Movement for 138- μ m Glass Beads with $v_0 = 0.443$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and Static-bed Height = 12 in.....	137

TABLE C.1. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.404$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.03	0.16	5.00
0.01	4.05	0.17	4.98
0.02	4.08	0.18	4.95
0.03	4.12	0.19	4.88
0.04	4.18	0.20	4.77
0.05	4.25	0.21	4.70
0.06	4.35	0.22	4.59
0.07	4.44	0.23	4.50
0.08	4.52	0.24	4.40
0.09	4.62	0.25	4.30
0.10	4.72	0.26	4.22
0.11	4.82	0.27	4.15
0.12	4.90	0.28	4.10
0.13	4.96	0.29	4.07
0.14	5.00	0.30	4.06
0.15	5.00	0.31	4.06

TABLE C.2. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.558$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.03	0.21	5.70
0.01	4.05	0.22	5.65
0.02	4.08	0.23	5.54
0.03	4.15	0.24	5.42
0.04	4.25	0.25	5.33
0.05	4.37	0.26	5.23
0.06	4.52	0.27	5.12
0.07	4.68	0.28	5.00
0.08	4.85	0.29	4.90
0.09	5.00	0.30	4.80
0.10	5.14	0.31	4.70
0.11	5.28	0.32	4.59
0.12	5.43	0.33	4.49
0.13	5.57	0.34	4.38
0.14	5.70	0.35	4.30
0.15	5.80	0.36	4.20
0.16	5.85	0.37	4.10
0.17	5.88	0.38	4.05
0.18	5.86	0.39	4.03
0.19	5.82	0.40	4.02
0.20	5.75		

TABLE C.3. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.704$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.04	0.25	6.15
0.01	4.06	0.26	6.07
0.02	4.12	0.27	5.97
0.03	4.21	0.28	5.86
0.04	4.36	0.29	5.73
0.05	4.55	0.30	5.62
0.06	4.76	0.31	5.50
0.07	5.00	0.32	5.35
0.08	5.18	0.33	5.23
0.09	5.38	0.34	5.10
0.10	5.60	0.35	4.98
0.11	5.80	0.36	4.88
0.12	5.98	0.37	4.80
0.13	6.18	0.38	4.75
0.14	6.36	0.39	4.70
0.15	6.50	0.40	4.67
0.16	6.62	0.41	4.60
0.17	6.69	0.42	4.54
0.18	6.78	0.43	4.45
0.19	6.78	0.44	4.30
0.20	6.62	0.45	4.20
0.21	6.53	0.46	4.14
0.22	6.45	0.47	4.10
0.23	6.37	0.48	4.04
0.24	6.25		

TABLE C.4. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.859 \text{ ft/sec}$, $t_{\text{on}} = 0.125 \text{ sec}$, $t_{\text{off}} = 0.375 \text{ sec}$, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.18	0.24	6.85
0.01	4.33	0.25	6.73
0.02	4.55	0.26	6.59
0.03	4.82	0.27	6.50
0.04	5.07	0.28	6.40
0.05	5.32	0.29	6.30
0.06	5.58	0.30	6.20
0.07	5.85	0.31	6.10
0.08	6.10	0.32	6.00
0.09	6.35	0.33	5.95
0.10	6.60	0.34	5.90
0.11	6.84	0.35	5.80
0.12	7.02	0.36	5.75
0.13	7.20	0.37	5.70
0.14	7.33	0.38	5.68
0.15	7.45	0.39	5.60
0.16	7.50	0.40	5.47
0.17	7.50	0.41	5.30
0.18	7.50	0.42	5.10
0.19	7.45	0.43	4.75
0.20	7.35	0.44	4.50
0.21	7.22	0.45	4.25
0.22	7.10	0.46	4.10
0.23	6.95	0.47	4.08

TABLE C.5. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.548$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.02	0.18	4.68
0.01	4.05	0.19	4.72
0.02	4.10	0.20	4.75
0.03	4.13	0.21	4.78
0.04	4.16	0.22	4.80
0.05	4.19	0.23	4.83
0.06	4.22	0.24	4.83
0.07	4.26	0.25	4.78
0.08	4.30	0.26	4.74
0.09	4.35	0.27	4.66
0.10	4.40	0.28	4.58
0.11	4.44	0.29	4.50
0.12	4.48	0.30	4.40
0.13	4.52	0.31	4.30
0.14	4.55	0.32	4.20
0.15	4.58	0.33	4.12
0.16	4.62	0.34	4.05
0.17	4.65	0.35	4.00

TABLE C.6. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.731$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.20	5.60
0.01	4.05	0.21	5.65
0.02	4.10	0.22	5.73
0.03	4.16	0.23	5.78
0.04	4.22	0.24	5.80
0.05	4.30	0.25	5.80
0.06	4.40	0.26	5.77
0.07	4.49	0.27	5.70
0.08	4.60	0.28	5.63
0.09	4.68	0.29	5.53
0.10	4.77	0.30	5.43
0.11	4.85	0.31	5.35
0.12	4.93	0.32	5.23
0.13	5.00	0.33	5.13
0.14	5.10	0.34	4.95
0.15	5.16	0.35	4.75
0.16	5.22	0.36	4.50
0.17	5.28	0.37	4.30
0.18	5.36	0.38	4.13
0.19	5.51	0.39	3.97

TABLE C.7. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.837 \text{ ft/sec}$, $t_{\text{on}} = 0.25 \text{ sec}$, $t_{\text{off}} = 0.25 \text{ sec}$, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.14	0.26	6.25
0.01	4.17	0.27	6.25
0.02	4.22	0.28	6.23
0.03	4.27	0.29	6.20
0.04	4.32	0.30	6.17
0.05	4.38	0.31	6.10
0.06	4.46	0.32	6.03
0.07	4.55	0.33	5.97
0.08	4.65	0.34	5.89
0.09	4.74	0.35	5.78
0.10	4.85	0.36	5.60
0.11	4.93	0.37	5.50
0.12	5.02	0.38	5.35
0.13	5.12	0.39	5.15
0.14	5.23	0.40	5.00
0.15	5.33	0.41	4.75
0.16	5.43	0.42	4.65
0.17	5.50	0.43	4.35
0.18	5.60	0.44	4.20
0.19	5.70	0.45	4.15
0.20	5.80	0.46	4.15
0.21	5.90	0.47	4.15
0.22	6.00	0.48	4.15
0.23	6.07	0.49	4.06
0.24	6.15	0.50	4.05
0.25	6.22		

TABLE C.8. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.992 \text{ ft/sec}$, $t_{\text{on}} = 0.25 \text{ sec}$, $t_{\text{off}} = 0.25 \text{ sec}$, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.35	0.24	7.13
0.01	4.41	0.25	7.21
0.02	4.47	0.26	7.24
0.03	4.54	0.27	7.21
0.04	4.65	0.28	7.19
0.05	4.74	0.29	7.15
0.06	4.85	0.30	7.06
0.07	4.95	0.31	6.95
0.08	5.06	0.32	6.83
0.09	5.18	0.33	6.67
0.10	5.29	0.34	6.49
0.11	5.42	0.35	6.29
0.12	5.55	0.36	6.06
0.13	5.68	0.37	5.82
0.14	5.82	0.38	5.62
0.15	5.96	0.39	5.37
0.16	6.11	0.40	5.12
0.17	6.24	0.41	4.87
0.18	6.40	0.42	4.68
0.19	6.54	0.43	4.54
0.20	6.67	0.44	4.30
0.21	6.80	0.45	4.23
0.22	6.92	0.46	4.23
0.23	7.03		

TABLE C.9. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.406 \text{ ft/sec}$, $t_{\text{on}} = 0.125 \text{ sec}$, $t_{\text{off}} = 0.375 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.05	0.16	9.10
0.01	8.07	0.17	9.05
0.02	8.10	0.18	8.97
0.03	8.19	0.19	8.90
0.04	8.28	0.20	8.82
0.05	8.40	0.21	8.74
0.06	8.50	0.22	8.67
0.07	8.60	0.23	8.62
0.08	8.70	0.24	8.52
0.09	8.80	0.25	8.43
0.10	8.90	0.26	8.35
0.11	9.00	0.27	8.25
0.12	9.08	0.28	8.18
0.13	9.12	0.29	8.12
0.14	9.15	0.30	8.04
0.15	9.13	0.31	8.00

TABLE C.10. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.504 \text{ ft/sec}$, $t_{\text{on}} = 0.125 \text{ sec}$, $t_{\text{off}} = 0.375 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.07	0.19	9.55
0.01	8.15	0.20	9.48
0.02	8.23	0.21	9.41
0.03	8.32	0.22	9.35
0.04	8.42	0.23	9.25
0.05	8.55	0.24	9.17
0.06	8.65	0.25	9.08
0.07	8.80	0.26	9.00
0.08	8.94	0.27	8.95
0.09	9.05	0.28	8.85
0.10	9.18	0.29	8.75
0.11	9.30	0.30	8.62
0.12	9.43	0.31	8.50
0.13	9.55	0.32	8.40
0.14	9.62	0.33	8.30
0.15	9.68	0.34	8.23
0.16	9.68	0.35	8.15
0.17	9.65	0.36	8.05
0.18	9.61	0.37	8.00

TABLE C.11. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.588$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.17	0.21	9.83
0.01	8.22	0.22	9.75
0.02	8.30	0.23	9.65
0.03	8.42	0.24	9.57
0.04	8.54	0.25	9.48
0.05	8.67	0.26	9.37
0.06	8.80	0.27	9.27
0.07	8.96	0.28	9.16
0.08	9.10	0.29	9.08
0.09	9.29	0.30	9.00
0.10	9.48	0.31	8.90
0.11	9.65	0.32	8.80
0.12	9.80	0.33	8.68
0.13	9.90	0.34	8.59
0.14	10.03	0.35	8.49
0.15	10.13	0.36	8.37
0.16	10.19	0.37	8.28
0.17	10.17	0.38	8.15
0.18	10.10	0.39	8.07
0.19	10.02	0.40	8.02
0.20	9.93	0.41	8.00

TABLE C.12. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.714 \text{ ft/sec}$, $t_{\text{on}} = 0.125 \text{ sec}$, $t_{\text{off}} = 0.375 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.36	0.26	10.35
0.01	8.42	0.27	10.26
0.02	8.52	0.28	10.17
0.03	8.65	0.29	10.08
0.04	8.80	0.30	10.00
0.05	8.96	0.31	9.90
0.06	9.12	0.32	9.82
0.07	9.35	0.33	9.74
0.08	9.50	0.34	9.66
0.09	9.75	0.35	9.58
0.10	10.00	0.36	9.48
0.11	10.23	0.37	9.38
0.12	10.45	0.38	9.28
0.13	10.65	0.39	9.20
0.14	10.85	0.40	9.10
0.15	11.00	0.41	9.00
0.16	11.08	0.42	8.91
0.17	11.12	0.43	8.80
0.18	11.12	0.44	8.70
0.19	11.09	0.45	8.60
0.20	11.02	0.46	8.55
0.21	10.92	0.47	8.49
0.22	10.82	0.48	8.44
0.23	10.70	0.49	8.39
0.24	10.52	0.50	8.36
0.25	10.45		

TABLE C.13. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.834$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.78	0.27	11.30
0.01	8.95	0.28	11.17
0.02	9.13	0.29	11.03
0.03	9.30	0.30	10.90
0.04	9.52	0.31	10.80
0.05	9.72	0.32	10.70
0.06	9.95	0.33	10.58
0.07	10.20	0.34	10.50
0.08	10.37	0.35	10.35
0.09	10.65	0.36	10.27
0.10	10.90	0.37	10.17
0.11	11.17	0.38	10.10
0.12	11.40	0.39	10.00
0.13	11.60	0.40	9.92
0.14	11.75	0.41	9.80
0.15	Bubble	0.42	9.70
		0.43	9.60
		0.44	9.50
		0.45	9.40
		0.46	9.32
		0.47	9.20
0.21	Bubble	0.48	9.12
0.22	11.77	0.49	9.02
0.23	11.68	0.50	8.90
0.24	11.60	0.51	8.83
0.25	11.50	0.52	8.80
0.26	11.40		

TABLE C.14. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.549$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.07	0.13	8.60	0.26	8.81
0.01	8.09	0.14	8.65	0.27	8.72
0.02	8.12	0.15	8.68	0.28	8.63
0.03	8.15	0.16	8.73	0.29	8.53
0.04	8.18	0.17	8.78	0.30	8.46
0.05	8.23	0.18	8.82	0.31	8.37
0.06	8.28	0.19	8.85	0.32	8.30
0.07	8.33	0.20	8.87	0.33	8.23
0.08	8.37	0.21	8.91	0.34	8.17
0.09	8.42	0.22	8.94	0.35	8.12
0.10	8.46	0.23	8.94	0.36	8.08
0.11	8.51	0.24	8.91	0.37	8.07
0.12	8.56	0.25	8.86		

TABLE C.15. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.767$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.30	0.17	9.56	0.34	9.30
0.01	8.33	0.18	9.65	0.35	9.22
0.02	8.37	0.19	9.73	0.36	9.13
0.03	8.43	0.20	9.82	0.37	9.04
0.04	8.50	0.21	9.91	0.38	8.95
0.05	8.58	0.22	10.00	0.39	8.86
0.06	8.66	0.23	10.03	0.40	8.79
0.07	8.73	0.24	10.05	0.41	8.72
0.08	8.81	0.25	10.03	0.42	8.65
0.09	8.88	0.26	10.00	0.43	8.58
0.10	8.96	0.27	9.96	0.44	8.40
0.11	9.04	0.28	9.91	0.45	8.30
0.12	9.12	0.29	9.85	0.46	8.24
0.13	9.20	0.30	9.75	0.47	8.18
0.14	9.28	0.31	9.63	0.48	8.15
0.15	9.36	0.32	9.50		
0.16	9.42	0.33	9.40		

TABLE C.16. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.856$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.55	0.16	9.88	0.32	9.65
0.01	8.57	0.17	10.00	0.33	9.55
0.02	8.60	0.18	10.10	0.34	9.47
0.03	8.66	0.19	10.20	0.35	9.42
0.04	8.73	0.20	10.26	0.36	9.30
0.05	8.82	0.21	10.30	0.37	9.25
0.06	8.92	0.22	10.30	0.38	9.18
0.07	9.02	0.23	10.30	0.39	9.10
0.08	9.10	0.24	10.25	0.40	9.05
0.09	9.18	0.25	10.20	0.41	8.93
0.10	9.28	0.26	10.13	0.42	8.87
0.11	9.37	0.27	10.05	0.43	8.80
0.12	9.47	0.28	9.97	0.44	8.73
0.13	9.57	0.29	9.90	0.45	8.68
0.14	9.68	0.30	9.82	0.46	8.65
0.15	9.78	0.31	9.72	0.47	8.65

TABLE C.17. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 1.05$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.85	0.18	11.50	0.36	9.90
0.01	8.88	0.19	11.62	0.37	Bubble
0.02	8.93	0.20	11.75		
0.03	9.02	0.21	11.85		
0.04	9.16	0.22	11.95		
0.05	9.28	0.23	11.90		
0.06	9.43	0.24	Bubble	0.42	Bubble
0.07	9.60			0.43	9.78
0.08	9.80			0.44	9.66
0.09	9.95	0.27	Bubble	0.45	9.53
0.10	10.15	0.28	10.56	0.46	9.40
0.11	10.35	0.29	10.48	0.47	9.28
0.12	10.55	0.30	10.38	0.48	9.15
0.13	10.75	0.31	10.30	0.49	9.06
0.14	10.90	0.32	10.23	0.50	8.97
0.15	11.10	0.33	10.15	0.51	8.88
0.16	11.20	0.34	10.06	0.52	8.83
0.17	11.37	0.35	9.97	0.53	8.80

TABLE C.18. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.318$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.10	0.14	8.92	0.28	9.34
0.01	8.13	0.15	8.98	0.29	9.25
0.02	8.17	0.16	9.03	0.30	9.10
0.03	8.20	0.17	9.11	0.31	9.00
0.04	8.25	0.18	9.18	0.32	8.87
0.05	8.32	0.19	9.23	0.33	8.77
0.06	8.38	0.20	9.28	0.34	8.67
0.07	8.45	0.21	9.34	0.35	8.57
0.08	8.52	0.22	9.38	0.36	8.48
0.09	8.58	0.23	9.40	0.37	8.38
0.10	8.66	0.24	9.45	0.38	8.30
0.11	8.72	0.25	9.46	0.39	8.25
0.12	8.78	0.26	9.45	0.40	8.23
0.13	8.85	0.27	9.40		

TABLE C.19. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.434$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.75$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.50	0.19	10.03	0.38	9.75
0.01	8.53	0.20	10.15	0.39	9.68
0.02	8.57	0.21	10.28	0.40	9.58
0.03	8.62	0.22	10.40	0.41	9.45
0.04	8.66	0.23	10.52	0.42	9.30
0.05	8.70	0.24	10.64	0.43	9.20
0.06	8.76	0.25	10.72	0.44	9.10
0.07	8.85	0.26	10.75	0.45	9.00
0.08	8.92	0.27	10.70	0.46	8.93
0.09	8.99	0.28	10.65	0.47	8.87
0.10	9.07	0.29	10.58	0.48	8.85
0.11	9.15	0.30	10.50	0.49	8.80
0.12	9.24	0.31	10.45	0.50	8.72
0.13	9.32	0.32	10.35	0.51	8.65
0.14	9.44	0.33	10.27	0.52	8.60
0.15	9.54	0.34	10.15	0.53	8.57
0.16	9.65	0.35	10.07	0.54	8.54
0.17	9.77	0.36	9.97	0.55	8.50
0.18	9.90	0.37	9.88		

TABLE C.20. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.536 \text{ ft/sec}$, $t_{\text{on}} = 0.25 \text{ sec}$, $t_{\text{off}} = 0.75 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.56	0.23	11.62	0.45	10.20
0.01	8.60	0.24	11.74	0.46	10.10
0.02	8.67	0.25	11.86	0.47	10.00
0.03	8.75	0.26	11.90	0.48	9.85
0.04	8.83	0.27	11.90	0.49	9.76
0.05	8.95	0.28	11.90	0.50	9.62
0.06	9.07	0.29	11.80	0.51	9.48
0.07	9.20	0.30	11.70	0.52	9.35
0.08	9.30	0.31	11.60	0.53	9.25
0.09	9.40	0.32	11.50	0.54	9.17
0.10	9.53	0.33	11.42	0.55	9.10
0.11	9.68	0.34	11.35	0.56	9.05
0.12	9.82	0.35	11.25	0.57	9.00
0.13	10.00	0.36	11.15	0.58	8.93
0.14	10.16	0.37	11.05	0.59	8.89
0.15	10.32	0.38	10.95	0.60	8.85
0.16	10.48	0.39	10.85	0.61	8.77
0.17	10.63	0.40	10.75	0.62	8.72
0.18	10.80	0.41	10.65	0.63	8.68
0.19	10.95	0.42	10.50	0.64	8.60
0.20	11.10	0.43	10.40	0.65	8.58
0.21	11.28	0.44	10.30	0.66	8.56
0.22	11.45				

TABLE C.21. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.588 \text{ ft/sec}$, $t_{\text{on}} = 0.25 \text{ sec}$, $t_{\text{off}} = 0.75 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.50	0.24	12.45	0.48	11.42
0.01	8.55	0.25	12.70	0.49	11.28
0.02	8.60	0.26	12.85	0.50	11.16
0.03	8.66	0.27	13.00	0.51	11.07
0.04	8.76	0.28	13.12	0.52	10.93
0.05	8.90	0.29	13.15	0.53	10.80
0.06	9.06	0.30	13.15	0.54	10.67
0.07	9.20	0.31	13.15	0.55	10.55
0.08	9.35	0.32	13.07	0.56	10.40
0.09	9.50	0.33	12.95	0.57	10.22
0.10	9.65	0.34	12.85	0.58	10.05
0.11	9.85	0.35	12.75	0.59	9.90
0.12	10.03	0.36	12.60	0.60	9.65
0.13	10.23	0.37	12.50	0.61	9.40
0.14	10.40	0.38	12.46	0.62	9.20
0.15	10.60	0.39	12.36	0.63	9.05
0.16	10.80	0.40	12.27	0.64	8.95
0.17	11.00	0.41	12.18	0.65	8.80
0.18	11.20	0.42	12.05	0.66	8.70
0.19	11.40	0.43	11.95	0.67	8.65
0.20	11.63	0.44	11.85	0.68	8.60
0.21	11.85	0.45	11.75	0.69	8.55
0.22	12.04	0.46	11.62	0.70	8.50
0.23	12.25	0.47	11.52		

TABLE C.22. Bed Movement for 580- μ m Glass Beads, with
 $v_0 = 0.514$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.20	0.15	13.33
0.01	12.35	0.16	13.27
0.02	12.45	0.17	13.20
0.03	12.53	0.18	13.12
0.04	12.63	0.19	13.02
0.05	12.73	0.20	12.93
0.06	12.84	0.21	12.85
0.07	12.94	0.22	12.77
0.08	13.05	0.23	12.67
0.09	13.15	0.24	12.58
0.10	13.25	0.25	12.53
0.11	13.33	0.26	12.45
0.12	13.38	0.27	12.35
0.13	13.40	0.28	12.25
0.14	13.38		

TABLE C.23. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.638$ ft/sec, $t_{on} = 0.125$ sec, $t_{off} = 0.375$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.40	0.20	13.94
0.01	12.43	0.21	13.85
0.02	12.52	0.22	13.76
0.03	12.64	0.23	13.66
0.04	12.77	0.24	13.56
0.05	12.92	0.25	13.46
0.06	13.07	0.26	13.37
0.07	13.23	0.27	13.28
0.08	13.38	0.28	13.21
0.09	13.55	0.29	13.13
0.10	13.70	0.30	13.06
0.11	13.85	0.31	12.93
0.12	14.00	0.32	12.85
0.13	14.10	0.33	12.75
0.14	14.18	0.34	12.65
0.15	14.23	0.35	12.60
0.16	14.23	0.36	12.50
0.17	14.20	0.37	12.40
0.18	14.12	0.38	12.35
0.19	14.03	0.39	12.35

TABLE C.24. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.770 \text{ ft/sec}$, $t_{\text{on}} = 0.125 \text{ sec}$, $t_{\text{off}} = 0.375 \text{ sec}$, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.50	0.15	15.00	0.30	13.75
0.01	12.65	0.16	15.00	0.31	13.72
0.02	12.80	0.17	14.95	0.32	13.60
0.03	12.97	0.18	14.88	0.33	13.50
0.04	13.17	0.19	14.78	0.34	13.38
0.05	13.36	0.20	14.67	0.35	13.25
0.06	13.55	0.21	14.55	0.36	13.10
0.07	13.77	0.22	14.46	0.37	13.00
0.08	13.97	0.23	14.37	0.38	12.90
0.09	14.17	0.24	14.25	0.39	12.80
0.10	14.38	0.25	14.15	0.40	12.70
0.11	14.56	0.26	14.05	0.41	12.60
0.12	14.73	0.27	13.95	0.42	12.50
0.13	14.88	0.28	13.88	0.43	12.45
0.14	14.95	0.29	13.82		

TABLE C.25. Bed Movement for 580- μm Glass Beads with
 $v_0 = 0.834 \text{ ft/sec}$, $t_{\text{on}} = 0.125 \text{ sec}$, $t_{\text{off}} = 0.375 \text{ sec}$, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.50	0.17	15.83	0.34	14.25
0.01	12.48	0.18	15.83	0.35	14.20
0.02	12.78	0.19	15.80	0.36	14.10
0.03	12.95	0.20	15.70	0.37	13.95
0.04	13.17	0.21	15.60	0.38	13.85
0.05	13.40	0.22	15.45	0.39	13.70
0.06	13.65	0.23	15.30	0.40	13.55
0.07	13.90	0.24	15.15	0.41	13.45
0.08	14.15	0.25	15.05	0.42	13.32
0.09	14.40	0.26	14.95	0.43	13.20
0.10	14.65	0.27	14.85	0.44	13.12
0.11	14.90	0.28	14.75	0.45	12.98
0.12	15.15	0.29	14.68	0.46	12.90
0.13	15.37	0.30	14.57	0.47	12.85
0.14	15.55	0.31	14.48	0.48	12.80
0.15	15.70	0.32	14.42	0.49	12.78
0.16	15.80	0.33	14.35		

TABLE C.26. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.500$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.14	0.11	12.50	0.22	12.74
0.01	12.16	0.12	12.52	0.23	12.68
0.02	12.18	0.13	12.57	0.24	12.61
0.03	12.22	0.14	12.60	0.25	12.55
0.04	12.25	0.15	12.63	0.26	12.47
0.05	12.30	0.16	12.67	0.27	12.40
0.06	12.35	0.17	12.72	0.28	12.32
0.07	12.38	0.18	12.75	0.29	12.25
0.08	12.40	0.19	12.78	0.30	12.17
0.09	12.43	0.20	12.78	0.31	12.12
0.10	12.47	0.21	12.76		

TABLE C.27. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.798$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.34	0.15	13.39	0.30	13.53
0.01	12.38	0.16	13.47	0.31	13.44
0.02	12.43	0.17	13.55	0.32	13.33
0.03	12.48	0.18	13.65	0.33	13.24
0.04	12.56	0.19	13.73	0.34	13.13
0.05	12.63	0.20	13.80	0.35	13.02
0.06	12.70	0.21	13.88	0.36	12.93
0.07	12.77	0.22	13.93	0.37	12.82
0.08	12.85	0.23	13.95	0.38	12.70
0.09	12.92	0.24	13.95	0.39	12.58
0.10	13.00	0.25	13.90	0.40	12.50
0.11	13.07	0.26	13.85	0.41	12.40
0.12	13.15	0.27	13.77	0.42	12.37
0.13	13.24	0.28	13.70	0.43	12.35
0.14	13.32	0.29	13.62	0.44	12.34

TABLE C.28. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 0.907$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.33	0.26	14.73
0.01	12.38	0.27	14.70
0.02	12.46	0.28	14.65
0.03	12.56	0.29	14.57
0.04	12.66	0.30	14.48
0.05	12.77	0.31	14.40
0.06	12.88	0.32	14.30
0.07	13.00	0.33	14.20
0.08	13.10	0.34	14.08
0.09	13.22	0.35	13.97
0.10	13.32	0.36	13.87
0.11	13.43	0.37	13.74
0.12	13.53	0.38	13.63
0.13	13.62	0.39	13.52
0.14	13.73	0.40	13.40
0.15	13.82	0.41	13.30
0.16	13.92	0.42	13.18
0.17	14.02	0.43	13.07
0.18	14.12	0.44	12.97
0.19	14.23	0.45	12.87
0.20	14.32	0.46	12.77
0.21	14.41	0.47	12.67
0.22	14.52	0.48	12.62
0.23	14.62	0.49	12.55
0.24	14.68	0.50	12.53
0.25	14.73		

TABLE C.29. Bed Movement for 580- μ m Glass Beads with
 $v_0 = 1.162$ ft/sec, $t_{on} = 0.25$ sec, $t_{off} = 0.25$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	13.10	0.27	16.87
0.01	13.15	0.28	16.82
0.02	13.24	0.29	16.75
0.03	13.35	0.30	16.66
0.04	13.50	0.31	16.56
0.05	13.67	0.32	16.46
0.06	13.88	0.33	16.35
0.07	14.03	0.34	16.25
0.08	14.23	0.35	16.13
0.09	14.43	0.36	16.03
0.10	14.60	0.37	15.92
0.11	14.76	0.38	15.80
0.12	14.93	0.39	15.65
0.13	15.07	0.40	15.53
0.14	15.24	0.41	15.38
0.15	15.40	0.42	15.24
0.16	15.55	0.43	15.03
0.17	15.70	0.44	14.82
0.18	15.86	0.45	14.52
0.19	16.00	0.46	14.32
0.20	16.15	0.47	13.95
0.21	16.32	0.48	13.75
0.22	16.47	0.49	13.40
0.23	16.62	0.50	13.28
0.24	16.73	0.51	13.18
0.25	16.82	0.52	13.10
0.26	16.87		

TABLE C.30. Bed Movement for 138- μm Glass Beads with
 $v_0 = 0.0786 \text{ ft/sec}$, $t_{\text{on}} = 0.2 \text{ sec}$, $t_{\text{off}} = 0.6 \text{ sec}$, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.28	4.69
0.02	4.06	0.30	4.67
0.04	4.13	0.32	Bubble
0.06	4.18		
0.08	4.24		
0.10	4.30		
0.12	4.37		
0.14	4.45	0.42	Bubble
0.16	4.54	0.44	4.35
0.18	4.62	0.46	4.18
0.20	4.68	0.48	4.13
0.22	4.70	0.50	4.04
0.24	4.70	0.52	4.00
0.26	4.70		

TABLE C.31. Bed Movement for 138- μm Glass Beads with
 $v_0 = 0.008 \text{ ft/sec}$, $t_{\text{on}} = 0.2 \text{ sec}$, $t_{\text{off}} = 0.6 \text{ sec}$, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.05	0.28	5.01
0.02	4.12	0.30	4.96
0.04	4.19	0.32	4.90
0.06	4.25	0.34	4.84
0.08	4.33	0.36	4.70
0.10	4.43	0.38	4.58
0.12	4.53	0.40	4.48
0.14	4.64	0.42	4.39
0.16	4.75	0.44	4.35
0.18	4.86	0.46	4.28
0.20	4.98	0.48	4.22
0.22	5.06	0.50	4.10
0.24	5.06	0.52	4.03
0.26	5.05	0.54	4.00

TABLE C.32. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.180$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.32	5.45
0.02	4.12	0.34	5.38
0.04	4.25	0.36	5.30
0.06	4.38	0.38	5.15
0.08	4.54	0.40	4.92
0.10	4.68	0.42	4.68
0.12	4.84	0.44	4.45
0.14	4.98	0.46	4.34
0.16	5.12	0.48	4.34
0.18	5.26	0.50	4.30
0.20	5.42	0.52	4.22
0.22	5.53	0.54	4.18
0.24	5.53	0.56	4.17
0.26	5.51	0.58	4.16
0.28	5.51	0.60	4.13
0.30	5.48	0.62	4.10

TABLE C.33. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.319$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.26	7.17
0.02	4.13	0.28	7.25
0.04	4.38	0.30	7.27
0.06	4.67	0.32	Bubble
0.08	5.00		
0.10	5.28		
0.12	5.58		
0.14	5.87	0.52	Bubble
0.16	6.13	0.54	4.30
0.18	6.45	0.56	4.10
0.20	6.77	0.58	4.06
0.22	7.03	0.60	4.04
0.24	7.17		

TABLE C.34. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.086$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.28	4.46
0.02	4.06	0.30	4.43
0.04	4.11	0.32	4.40
0.06	4.15	0.34	4.38
0.08	4.19	0.36	4.37
0.10	4.24	0.38	4.34
0.12	4.29	0.40	4.32
0.14	4.34	0.42	4.30
0.16	4.39	0.44	4.26
0.18	4.43	0.46	4.24
0.20	4.49	0.48	4.22
0.22	4.52	0.50	4.18
0.24	4.48	0.52	4.10
0.26	4.47	0.54	4.02

TABLE C.35. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.130$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.28	4.76
0.02	4.03	0.30	4.70
0.04	4.12	0.32	4.60
0.06	4.22	0.34	4.50
0.08	4.30	0.36	4.38
0.10	4.37	0.38	4.29
0.12	4.47	0.40	4.23
0.14	4.55	0.42	4.21
0.16	4.64	0.44	4.20
0.18	4.72	0.46	4.16
0.20	4.81	0.48	4.12
0.22	4.85	0.50	4.08
0.24	4.83	0.52	4.05
0.26	4.80	0.54	4.00

TABLE C.36. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.280$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.28	5.70
0.02	4.12	0.30	5.62
0.04	4.28	0.32	5.60
0.06	4.43	0.34	5.48
0.08	4.60	0.36	5.27
0.10	4.78	0.38	5.03
0.12	4.97	0.40	4.75
0.14	5.12	0.42	4.53
0.16	5.30	0.44	4.42
0.18	5.48	0.46	4.34
0.20	5.63	0.48	4.30
0.22	5.75	0.50	4.24
0.24	5.75	0.52	4.20
0.26	5.73		

TABLE C.37. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.447$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.32	Bubble
0.02	4.22	0.34	Bubble
0.04	4.42	0.36	6.87
0.06	4.67	0.38	6.83
0.08	4.95	0.40	6.75
0.10	5.25	0.42	6.57
0.12	5.52	0.44	6.20
0.14	5.78	0.46	5.90
0.16	6.05	0.48	Bubble
0.18	6.33		
0.20	6.60		
0.22	6.85		
0.24	6.95	0.60	Bubble
0.28	6.92	0.62	4.00
0.30	Bubble		

TABLE C.38. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.0907$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.26	4.31	0.52	4.37
0.02	4.04	0.28	4.33	0.54	4.28
0.04	4.06	0.30	4.36	0.56	4.24
0.06	4.08	0.32	4.38	0.58	4.20
0.08	4.10	0.34	4.42	0.60	4.13
0.10	4.12	0.36	4.45	0.62	4.10
0.12	4.14	0.38	4.48	0.64	4.08
0.14	4.16	0.40	4.51	0.66	4.06
0.16	4.19	0.42	4.53	0.68	4.06
0.18	4.22	0.44	4.53	0.70	4.06
0.20	4.24	0.46	4.53	0.72	4.05
0.22	4.26	0.48	4.52	0.74	4.05
0.24	4.28	0.50	4.48	0.76	4.04

TABLE C.39. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.161$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.05	0.36	5.00
0.02	4.08	0.38	5.08
0.04	4.13	0.40	5.14
0.06	4.17	0.42	5.18
0.08	4.21	0.44	5.25
0.10	4.25	0.46	Bubble
0.12	4.29		
0.14	4.33		
0.16	4.38		
0.18	4.45	0.62	Bubble
0.20	4.50	0.64	4.35
0.22	4.55	0.66	4.27
0.24	4.61	0.68	4.20
0.26	4.67	0.70	4.16
0.28	4.73	0.72	4.15
0.30	4.80	0.74	4.13
0.32	4.87	0.76	4.10
0.34	4.92	0.78	4.05

TABLE C.40. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.290$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.05	0.30	5.88
0.02	4.13	0.32	6.05
0.04	4.23	0.34	6.25
0.06	4.33	0.36	6.40
0.08	4.44	0.38	Bubble
0.10	4.55		
0.12	4.67		
0.14	4.78		
0.16	4.90	0.66	Bubble
0.18	5.03	0.68	4.25
0.20	5.13	0.70	4.15
0.22	5.25	0.72	4.15
0.24	5.40	0.74	4.10
0.26	5.55	0.76	3.95
0.28	5.70	0.78	3.90

TABLE C.41. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.396$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 4 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	4.00	0.24	5.96
0.02	4.13	0.26	6.13
0.04	4.27	0.28	6.28
0.06	4.42	0.30	6.40
0.08	4.57	0.32	6.48
0.10	4.75	0.34	6.60
0.12	4.93	0.36	Bubble
0.14	5.10		
0.16	5.25		
0.18	5.40		
0.20	5.60	0.72	Bubble
0.22	5.77	0.74	4.00

TABLE C.42. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.068$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.08	0.32	8.36	0.64	8.32
0.02	8.10	0.34	8.38	0.66	8.31
0.04	8.12	0.36	8.40	0.68	8.30
0.06	8.13	0.38	8.42	0.70	8.30
0.08	8.15	0.40	8.44	0.72	8.29
0.10	8.17	0.42	8.45	0.74	8.28
0.12	8.18	0.44	8.43	0.76	8.27
0.14	8.19	0.46	8.42	0.78	8.25
0.16	8.20	0.48	8.40	0.80	8.20
0.18	8.22	0.50	8.38	0.82	8.15
0.20	8.24	0.52	8.37	0.84	8.10
0.22	8.26	0.54	8.36	0.86	8.08
0.24	8.28	0.56	8.36	0.88	8.06
0.26	8.30	0.58	8.35	0.90	8.05
0.28	8.32	0.60	8.35		
0.30	8.34	0.62	8.34		

TABLE C.43. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.163$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.05	0.34	8.93	0.68	9.15
0.02	8.12	0.36	8.97	0.70	9.12
0.04	8.17	0.38	9.03	0.72	9.08
0.06	8.22	0.40	9.08	0.74	9.00
0.08	8.25	0.42	9.16	0.76	8.93
0.10	8.30	0.44	9.22	0.78	8.75
0.12	8.34	0.46	9.27	0.80	8.58
0.14	8.38	0.48	9.32	0.82	8.35
0.16	8.44	0.50	9.32	0.84	8.23
0.18	8.49	0.52	9.27	0.86	8.18
0.20	8.55	0.54	9.27	0.88	8.13
0.22	8.60	0.56	9.27	0.90	8.11
0.24	8.65	0.58	9.25	0.92	8.10
0.26	8.70	0.60	9.23	0.94	8.08
0.28	8.75	0.62	9.22	0.96	8.06
0.30	8.80	0.64	9.20		
0.32	8.85	0.66	9.18		

TABLE C.44. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.259$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.10	0.42	10.15
0.02	8.18	0.44	10.25
0.04	8.28	0.46	10.36
0.06	8.37	0.48	10.45
0.08	8.47	0.50	10.45
0.10	8.55	0.52	10.42
0.12	8.65	0.54	10.37
0.14	8.75	0.56	10.37
0.16	8.83	0.58	10.37
0.18	8.93	0.60	10.37
0.20	9.05	0.62	10.37
0.22	9.15	0.64	10.37
0.24	9.25	0.68	10.37
0.26	9.36	0.70	10.40
0.28	9.47	0.72	10.40
0.30	9.56	0.74	Bubble
0.32	9.66		
0.34	9.75		
0.36	9.85		
0.38	9.95	0.92	Bubble
0.40	10.05	0.94	8.10

TABLE C.45. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.396$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.06	0.48	12.40
0.02	8.15	0.50	12.60
0.04	8.35	0.52	12.80
0.06	8.50	0.54	12.80
0.08	8.65	0.56	12.70
0.10	8.80	0.58	12.60
0.12	8.97	0.60	Bubble
0.14	9.12		
0.16	9.30		
0.18	9.48		
0.20	9.64	0.76	Bubble
0.22	9.80	0.78	8.50
0.24	10.00	0.80	8.47
0.26	10.16	0.82	8.43
0.28	10.35	0.84	8.38
0.30	10.52	0.86	8.35
0.32	10.70	0.88	8.32
0.34	10.90	0.90	8.30
0.36	11.06	0.92	8.25
0.38	11.26	0.94	8.25
0.40	11.50	0.96	8.20
0.42	11.75	0.98	9.20
0.44	12.00	1.00	8.10
0.46	12.20		

TABLE C.46. Bed Movement for 138- μm Glass Beads with
 $v_0 = 0.118 \text{ ft/sec}$, $t_{\text{on}} = 0.2 \text{ sec}$, $t_{\text{off}} = 0.4 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.38	0.32	8.80
0.02	8.42	0.34	8.73
0.04	8.48	0.36	8.68
0.06	8.56	0.38	8.63
0.08	8.62	0.40	8.60
0.10	8.67	0.42	8.57
0.12	8.73	0.44	8.55
0.14	8.80	0.46	8.52
0.16	8.85	0.48	8.51
0.18	8.91	0.50	8.48
0.20	8.95	0.52	8.46
0.22	8.97	0.54	8.44
0.24	8.95	0.56	8.42
0.26	8.92	0.58	8.40
0.28	8.90	0.60	8.38
0.30	8.86		

TABLE C.47. Bed Movement for 138- μm Glass Beads with
 $v_0 = 0.178 \text{ ft/sec}$, $t_{\text{on}} = 0.2 \text{ sec}$, $t_{\text{off}} = 0.4 \text{ sec}$, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.90	0.24	9.83
0.02	8.98	0.26	Bubble
0.04	9.13		
0.06	9.26		
0.08	9.40		
0.10	9.53	0.30	Bubble
0.12	9.75	0.32	9.20
0.14	9.85	0.34	9.05
0.16	10.00	0.36	8.98
0.18	10.03	0.38	8.90
0.20	10.12	0.40	8.85
0.22	9.90		

TABLE C.48. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.403$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	10.42	0.20	11.93
0.02	10.58	0.22	11.65
0.04	10.92	0.24	11.20
0.06	11.20	0.26	10.70
0.08	11.40	0.28	10.40
0.10	11.62	0.30	10.38
0.12	11.82	0.32	10.38
0.14	12.00	0.34	10.40
0.16	12.06	0.36	10.42
0.18	12.06	0.38	10.45

TABLE C.49. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.050$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	7.97	0.40	8.24
0.02	8.02	0.42	8.23
0.04	8.06	0.44	8.22
0.06	8.12	0.46	8.21
0.08	8.17	0.48	8.19
0.10	8.22	0.50	8.18
0.12	8.27	0.52	8.17
0.14	8.32	0.54	8.16
0.16	8.37	0.56	8.14
0.18	8.40	0.58	8.13
0.20	8.38	0.60	8.12
0.22	8.36	0.62	8.10
0.24	8.34	0.64	8.08
0.26	8.34	0.66	8.06
0.28	8.34	0.68	8.04
0.30	8.32	0.70	8.03
0.32	8.31	0.72	8.02
0.34	8.29	0.74	8.01
0.36	8.27	0.76	8.00
0.38	8.26		

TABLE C.50. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.114$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.55	0.24	9.47	0.48	8.74
0.02	8.63	0.26	9.46	0.50	8.74
0.04	8.75	0.28	9.45	0.52	8.73
0.06	8.87	0.30	9.43	0.54	8.70
0.08	8.93	0.32	9.38	0.56	8.67
0.10	9.02	0.34	9.32	0.58	8.65
0.12	9.13	0.36	9.22	0.60	8.62
0.14	9.23	0.38	9.00	0.62	8.58
0.16	9.33	0.40	8.83	0.64	8.57
0.18	9.44	0.42	8.70	0.66	8.55
0.20	9.52	0.44	8.68	0.68	8.53
0.22	9.53	0.46	8.72		

TABLE C.51. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.223$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.10	0.30	9.75	0.60	9.65
0.02	8.33	0.32	9.75	0.62	9.65
0.04	8.55	0.34	9.72	0.64	9.65
0.06	8.70	0.36	9.72	0.66	9.65
0.08	8.87	0.38	9.72	0.68	9.70
0.10	9.07	0.40	9.72	0.70	9.73
0.12	9.28	0.42	9.70	0.72	9.77
0.14	9.50	0.44	9.70	0.74	Bubble
0.16	9.70	0.46	9.68		
0.18	9.87	0.48	9.68		
0.20	9.87	0.50	9.66		
0.22	9.83	0.52	9.66	0.78	Bubble
0.24	9.75	0.54	9.66	0.80	8.40
0.26	9.75	0.56	9.65		
0.28	9.75	0.58	0.65		

TABLE C.52. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.330$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 8 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	8.77	0.20	10.53	0.60	10.60
0.02	8.85	0.22	10.53	0.62	10.60
0.04	9.05	0.24	10.53	0.64	10.57
0.06	9.36	0.26	10.56	0.66	10.48
0.08	9.72			0.68	10.20
0.10	10.03			0.70	9.90
0.12	10.37			0.72	9.45
0.14	10.62	0.54	10.56	0.74	8.95
0.16	10.65	0.56	10.60	0.76	8.55
0.18	10.60	0.58	10.60	0.78	8.50

TABLE C.53. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.057$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.08	0.26	12.45	0.52	12.36
0.02	12.12	0.28	12.45	0.54	12.35
0.04	12.19	0.30	12.45	0.56	12.34
0.06	12.26	0.32	12.44	0.58	12.32
0.08	12.31	0.34	12.44	0.60	12.28
0.10	12.35	0.36	12.44	0.62	12.25
0.12	12.38	0.38	12.42	0.64	12.18
0.14	12.45	0.40	12.42	0.66	12.15
0.16	12.52	0.42	12.42	0.68	12.15
0.18	12.57	0.44	12.40	0.70	12.12
0.20	12.57	0.46	12.38	0.72	12.12
0.22	12.52	0.48	12.37	0.74	12.10
0.24	12.48	0.50	12.37		

TABLE C.54. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.142$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.60	0.28	13.55	0.56	12.77
0.02	12.67	0.30	13.57	0.58	12.77
0.04	12.82	0.32	13.60	0.60	12.77
0.06	12.95	0.34	13.62	0.62	12.82
0.08	13.07	0.36	13.63	0.64	12.82
0.10	13.16	0.38	13.63	0.66	12.80
0.12	13.24	0.40	13.63	0.68	12.75
0.14	13.34	0.42	13.62	0.70	12.72
0.16	13.45	0.44	13.55	0.72	12.68
0.18	13.57	0.46	13.45	0.74	12.68
0.20	13.67	0.48	13.18	0.76	12.66
0.22	13.69	0.50	13.04	0.78	12.65
0.24	13.65	0.52	12.93		
0.26	13.57	0.54	12.84		

TABLE C.55. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.273$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	13.87	0.22	16.22	0.44	15.40
0.02	13.95	0.24	16.12	0.46	15.00
0.04	14.22	0.26	16.01	0.48	14.30
0.06	14.51	0.28	15.95	0.50	14.26
0.08	14.75	0.30	15.95	0.52	14.00
0.10	14.95	0.32	16.00	0.54	13.98
0.12	15.08	0.34	16.00	0.56	13.95
0.14	15.30	0.36	15.97	0.58	13.92
0.16	15.52	0.38	15.88	0.60	13.88
0.18	15.76	0.40	15.75	0.62	13.87
0.20	16.00	0.42	15.58		

TABLE C.56. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.421$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.6$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	15.13	0.18	18.42	0.36	18.70
0.01	15.20	0.19	18.63	0.37	18.60
0.02	15.34	0.20	18.82	0.38	18.35
0.03	15.55	0.21	19.00	0.39	18.08
0.04	15.78	0.22	19.20	0.40	17.85
0.05	16.05	0.23	19.30	0.41	17.50
0.06	16.30	0.24	19.40	0.42	17.17
0.07	16.52	0.25	19.25	0.43	16.80
0.08	16.70	0.26	19.00	0.44	16.40
0.09	16.87	0.27	19.00	0.45	16.00
0.10	17.00	0.28	19.05	0.46	15.60
0.11	17.13	0.29	19.15	0.47	15.40
0.12	17.27	0.30	19.20	0.48	15.30
0.13	17.43	0.31	19.20	0.49	15.25
0.14	17.60	0.32	19.20	0.50	15.20
0.15	17.76	0.33	19.15	0.51	15.20
0.16	17.95	0.34	19.10	0.52	15.20
0.17	18.19	0.35	18.92	0.53	15.18

TABLE C.57. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.098$ ft/sec, $t_{on} = 0.2$ sec, $t_{off} = 0.4$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.38	0.20	12.95	0.40	12.65
0.02	12.48	0.22	12.92	0.42	12.60
0.04	12.55	0.24	12.87	0.44	12.55
0.06	12.60	0.26	12.85	0.46	12.50
0.08	12.65	0.28	12.83	0.48	12.46
0.10	12.70	0.30	12.80	0.50	12.43
0.12	12.77	0.32	12.72	0.52	12.40
0.14	12.85	0.34	12.70	0.54	12.37
0.16	12.92	0.36	12.70	0.56	12.33
0.18	12.95	0.38	12.73	0.60	12.30

TABLE C.58. Bed Movement for 138- μm Glass Beads with
 $v_0 = 0.208 \text{ ft/sec}$, $t_{\text{on}} = 0.2 \text{ sec}$, $t_{\text{off}} = 0.4 \text{ sec}$; and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.95	0.22	14.20	0.44	13.78
0.02	13.02	0.24	14.15	0.46	13.45
0.04	13.18	0.26	14.08	0.48	13.15
0.06	13.35	0.28	14.08	0.50	12.75
0.08	13.48	0.30	14.12	0.52	12.63
0.10	13.58	0.32	14.13	0.54	12.63
0.12	13.68	0.34	14.15	0.56	12.68
0.14	13.80	0.36	14.17	0.58	12.82
0.16	13.92	0.38	14.17	0.60	13.00
0.18	14.06	0.40	14.12		
0.20	14.17	0.42	13.97		

TABLE C.59. Bed Movement for 138- μm Glass Beads with
 $v_0 = 0.334 \text{ ft/sec}$, $t_{\text{on}} = 0.2 \text{ sec}$, $t_{\text{off}} = 0.4 \text{ sec}$, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	13.60	0.14	15.60	0.30	14.15
0.01	13.67	0.15	15.55	0.31	13.75
0.02	13.88	0.16	15.55	0.32	13.65
0.03	14.20	0.17	15.58	0.33	13.40
0.04	14.46	0.18	15.53	0.34	13.20
0.05	14.66	0.19	15.51	0.35	13.30
0.06	14.82			0.36	13.45
0.07	14.97			0.37	13.60
0.08	15.17			0.38	13.82
0.09	15.40	0.25	15.51	0.39	13.95
0.10	15.63	0.26	15.40	0.40	13.95
0.11	15.82	0.27	15.40	0.41	13.80
0.12	15.82	0.28	15.35	0.42	13.70
0.13	15.14	0.29	14.60		

TABLE C.60. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.90$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	12.38	0.32	12.75	0.64	12.60
0.02	12.40	0.34	12.78	0.66	12.57
0.04	12.43	0.36	12.82	0.68	12.55
0.06	12.46	0.38	12.86	0.70	12.52
0.08	12.48	0.40	12.90	0.72	12.52
0.10	12.50	0.42	12.90	0.74	12.50
0.12	12.52	0.44	12.90	0.76	12.50
0.14	12.54	0.46	12.90	0.78	12.48
0.16	12.57	0.48	12.90	0.80	12.47
0.18	12.59	0.50	12.86	0.82	12.47
0.20	12.62	0.52	12.77	0.84	12.45
0.22	12.63	0.54	12.67	0.86	12.45
0.24	12.65	0.56	12.65	0.88	12.43
0.26	12.67	0.58	12.65	0.90	12.42
0.28	12.69	0.60	12.65	0.92	12.41
0.30	12.72	0.62	12.63	0.94	12.40

TABLE C.61. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.200$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	13.52	0.28	14.48	0.56	13.67
0.02	13.62	0.30	14.38	0.58	13.72
0.04	13.72	0.32	14.20	0.60	13.72
0.06	13.82	0.34	14.00	0.62	13.72
0.08	13.88	0.36	13.75	0.64	13.72
0.10	13.94	0.38	13.65	0.66	13.72
0.12	14.02	0.40	13.55	0.68	13.70
0.14	14.20	0.42	13.55	0.70	13.70
0.16	14.28	0.44	13.55	0.72	13.70
0.18	14.38	0.46	13.65	0.74	13.70
0.20	14.47	0.48	13.73	0.76	13.70
0.22	14.55	0.50	13.73	0.78	13.67
0.24	14.58	0.52	13.70		
0.26	14.56	0.54	13.67		

TABLE C.62. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.272$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	14.65	0.32	14.60
0.02	14.80	0.34	14.50
0.04	14.95	0.36	14.45
0.06	15.08	0.38	14.35
0.08	15.20	0.40	14.30
0.10	15.37	0.42	14.45
0.12	15.58	0.44	14.75
0.14	15.85	0.46	14.90
0.16	16.05	0.48	14.90
0.18	16.15	0.50	14.85
0.20	16.30	0.52	14.80
0.22	16.25	0.54	14.65
0.24	16.05	0.56	14.60
0.26	15.85	0.58	14.60
0.28	15.40	0.60	14.60
0.30	14.80	0.62	14.65

TABLE C.63. Bed Movement for 138- μ m Glass Beads with
 $v_0 = 0.443$ ft/sec, $t_{on} = 0.5$ sec, $t_{off} = 0.5$ sec, and
 Static-bed Height = 12 in.

Time, sec	Bed Height, in.	Time, sec	Bed Height, in.
0.00	16.60	0.32	15.25
0.02	16.80	0.34	15.50
0.04	17.12	0.36	15.70
0.06	17.40	0.38	15.75
0.08	17.62	0.40	16.00
0.10	17.80	0.42	16.15
0.12	17.90	0.44	16.30
0.14	17.90	0.46	16.50
0.16	17.85	0.48	16.70
0.18	17.60	0.50	16.85
0.20	17.10	0.52	16.85
0.22	16.50	0.54	16.76
0.24	16.00	0.56	16.65
0.26	15.00	0.58	16.60
0.28	15.00	0.60	16.60
0.30	15.25		

APPENDIX D

Experimental Data for Heat-transfer Coefficients

In the tables in this appendix, the combinations of experimental variables are listed with their symbols. These symbols are defined as follows:

<u>Particle</u>	a) 580- μm glass beads	<u>Heater Length</u>	j) 0.5 in.
	b) 301- μm glass beads		k) 2.0 in.
	c) 138- μm glass beads		l) 4.0 in.
	d) 73- μm glass beads	<u>Heater Position</u>	m) 1 in.
	e) 292- μm aluminum shot		n) 3 in.
	f) 313- μm copper shot		o) 6 in.
<u>Gas</u>	g) air	<u>Static-bed Height</u>	p) 4 in.
	h) carbon dioxide		q) 8 in.
	i) helium		r) 12 in.

The following tables are contained in this appendix:

<u>No.</u>	<u>Title</u>	<u>Page</u>
D.1.	Data for Fluidized-bed Heat-transfer Coefficients.	139
D.2.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.125 sec and Off-period = 0.375 sec.	141
D.3.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.2 sec and Off-period = 0.4 sec.	142
D.4.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.2 sec and Off-period = 0.6 sec.	142
D.5.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.25 sec and Off-period = 0.25 sec	143
D.6.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.25 sec and Off-period = 0.50 sec	144
D.7.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.25 sec and Off-period = 0.75 sec	145
D.8.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.375 sec and Off-period = 0.375 sec.	145
D.9.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.5 sec and Off-period = 0.5 sec.	145
D.10.	Data for Pulsed-bed Heat-transfer Coefficients with On-period = 0.5 sec and Off-period = 1.0 sec.	145

TABLE D.1. Data for Fluidized-bed Heat-transfer Coefficients

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
1) a-g-j-o-r		7) a-g-k-o-r		0.278	168.3
0.988	55.6	1.20	52.2	0.384	173.2
1.081	67.0	1.256	55.4	0.480	173.2
1.187	71.4	1.40	60.5	0.555	177.2
1.320	81.9	1.53	62.4	0.623	178.2
1.461	81.3	1.69	63.4	0.748	181.1
1.560	80.3	1.81	64.2		
1.718	70.8			14) c-g-j-n-p	
2) a-g-j-o-q		8) a-g-l-n-r		0.174	108.1
0.927	40.5	1.085	27.7	0.276	134.2
0.990	57.7	1.118	34.6	0.399	149.8
0.999	62.5	1.200	39.5	0.522	159.2
1.305	77.1	1.288	41.2	0.592	161.3
1.552	74.7	1.388	42.2	0.641	164.5
1.845	72.1	1.454	42.5	0.727	165.0
		1.562	43.1	0.903	168.4
3) a-g-j-n-r		9) a-g-l-o-r		15) c-g-j-n-q	
0.987	46.3	1.041	30.9	0.115	67.8
1.023	55.8	1.102	36.6	0.155	97.3
1.120	67.2	1.177	40.2	0.281	132.3
1.230	69.8	1.344	42.4	0.397	152.9
1.36	72.0	1.442	41.9	0.473	160.3
1.395	72.5	1.590	40.7	0.593	165.4
1.574	71.0			0.711	169.7
1.725	69.4	10) b-g-j-o-q		0.831	171.5
1.906	69.7	0.276	32.9		
4) a-g-j-n-q		0.326	63.3	16) c-g-k-o-r	
0.917	32.3	0.377	81.6	0.127	66.8
0.958	58.4	0.452	95.8	0.162	84.5
1.015	68.0	0.537	104.1	0.284	115.5
1.078	74.4	0.692	109.2	0.415	123.0
1.133	81.2	0.793	106.9	0.481	125.1
1.331	81.4	0.909	106.2	0.585	124.4
1.500	79.9	1.015	105.7	0.667	123.9
1.712	73.0				
5) a-g-j-n-p		11) c-g-j-o-r		17) c-g-l-n-r	
0.930	21.0	0.113	86.9	0.0986	33.5
1.001	48.9	0.164	117.3	0.138	56.2
1.090	59.2	0.298	154.8	0.243	79.7
1.125	70.3	0.421	163.6	0.293	77.2
1.224	71.2	0.464	163.6	0.385	86.6
1.410	72.2	0.595	163.0	0.513	89.9
1.507	71.5	0.720	163.3	0.594	90.7
1.70	70.9				
6) a-g-j-m-q		12) c-g-j-n-r		18) c-g-l-o-r	
0.942	24.6	0.116	57.1	0.115	36.6
1.00	48.7	0.198	113.6	0.177	61.6
1.05	64.5	0.295	135.4	0.308	79.0
1.12	70.9	0.364	146.1	0.405	82.6
1.26	76.0	0.475	160.6	0.481	82.0
1.41	79.5	0.567	165.9	0.586	83.0
1.53	84.6	0.638	166.2	0.687	81.2
1.65	86.4	0.758	169.0		
1.96	86.4	13) c-g-j-m-r		19) c-g-l-n-q	
		0.110	65.1	0.120	45.3
		0.194	138.2	0.241	74.5
				0.387	86.2

TABLE D.1 (Contd.)

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
19) c-g-l-n-q (Contd.)		0.470	278.8	0.0382	115.1
0.433	95.9	0.556	288.7	0.458	122.3
0.544	99.7			0.552	126.3
0.676	97.8	22) d-g-j-o-r		0.619	127.9
0.793	96.9	0.051	54.0	0.708	122.3
		0.056	45.6	0.796	120.4
20) c-h-j-o-r		0.073	62.8	0.909	117.2
0.110	77.0	0.095	73.3		
0.155	98.9	0.112	103.9	24) t-g-j-o-q	
0.199	109.4	0.159	119.3	1.174	56.0
0.267	128.2	0.165	117.7	1.253	77.9
0.349	134.1	0.256	147.0	1.338	101.7
0.442	135.7	0.402	156.3	1.430	114.2
		0.418	160.1	1.583	118.6
21) c-i-j-o-r		0.514	166.9	1.696	120.0
0.097	117.3	0.581	167.7	1.816	118.6
0.160	177.9			1.955	115.6
0.209	203.8	23) e-g-j-o-q			
0.211	201.4	0.255	46.0		
0.313	245.0	0.281	77.5		

TABLE D.2. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.125 sec and Off-period = 0.375 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
25) a-g-j-o-r		29) a-g-j-n-p			
0.356	49.6	0.346	46.7	0.763	35.4
0.427	57.5	0.372	52.1	0.838	34.2
0.503	70.1	0.470	55.2		
0.521	64.8	0.529	64.0	34) g-b-j-o-q	
0.538	69.2	0.598	66.4	0.096	55.7
0.547	65.6	0.653	66.2	0.128	72.1
0.594	69.2	0.773	62.6	0.188	93.6
0.618	72.6			0.225	97.1
0.673	74.6	30) a-g-j-m-q		0.260	82.1
0.701	71.1	0.314	43.7	0.263	83.4
0.739	75.3	0.326	57.5	0.333	91.0
0.805	69.8	0.409	60.6	0.359	92.6
0.845	73.8	0.422	61.5	0.411	96.3
		0.455	66.6	0.453	102.9
26) a-g-j-o-q		0.503	72.4	0.537	104.3
0.312	45.2	0.591	72.4	0.565	106.5
0.389	64.0	0.655	71.8	0.622	112.4
0.452	66.8	0.766	71.8	0.677	114.5
0.460	69.0	0.876	70.3	0.726	114.6
0.559	69.3				
0.606	73.6	31) a-g-k-o-r		35) e-g-j-o-q	
0.676	74.4	0.415	37.9	0.100	57.0
0.678	74.5	0.462	40.7	0.133	72.1
0.737	79.0	0.544	43.0	0.183	91.6
0.778	78.8	0.616	45.3	0.237	91.6
0.856	84.0	0.652	49.1	0.296	91.6
		0.718	54.2	0.300	100.8
27) a-g-j-n-r		0.781	54.7	0.366	106.6
0.306	44.4			0.458	123.0
0.356	55.0	32) a-g-l-n-r		0.509	124.5
0.407	56.1	0.413	22.0		
0.453	63.2	0.504	25.9	36) f-g-j-o-q	
0.523	60.2	0.534	31.0	0.361	67.0
0.655	63.3	0.557	33.9	0.405	68.9
0.743	63.7	0.669	31.4	0.470	98.8
		0.751	32.2	0.504	99.3
28) a-g-j-n-q				0.566	101.0
0.360	52.7	33) a-g-l-o-r		0.610	104.0
0.426	64.2	0.477	23.5	0.667	121.4
0.469	67.0	0.548	29.6	0.751	128.3
0.534	74.8	0.611	32.9	0.801	131.6
0.601	73.4	0.646	35.2		
0.674	71.8	0.663	34.5		
0.785	61.7	0.712	36.0		

TABLE D.3. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.2 sec and Off-period = 0.4 sec.

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
37) c-g-j-o-r		0.256	68.3	42) c-h-j-o-r	
0.087	70.7	0.342	81.0	0.089	58.5
0.111	93.1	0.401	84.4	0.112	99.3
0.154	119.5			0.124	110.0
0.218	138.9	40) e-g-l-n-q		0.184	121.0
0.288	151.5	0.096	51.4	0.215	123.5
0.351	158.5	0.134	57.9	0.298	124.2
0.446	153.6	0.204	68.2		
		0.252	70.3	43) c-i-j-o-r	
38) c-g-k-o-r		0.323	83.6	0.065	149.7
0.077	64.4	0.364	87.6	0.127	233.2
0.112	93.6	0.414	89.2	0.174	275.6
0.129	105.9			0.221	288.7
0.149	98.0	41) c-g-l-o-r		0.267	307.0
0.171	96.9	0.088	43.7	0.367	326.0
0.245	111.8	0.126	65.4	0.453	337.0
0.317	113.3	0.205	69.1		
0.412	111.8	0.258	72.7		
39) c-g-l-n-r		0.330	74.1		
0.096	46.9	0.395	75.3		
0.148	62.4	0.460	77.8		

TABLE D.4. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.2 sec and Off-period = 0.6 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
44) c-g-j-o-r		48) c-g-j-n-q		0.352	90.2
0.127	116.9	0.082	72.6	0.402	87.9
0.218	152.0	0.114	105.9		
0.268	160.2	0.178	131.9	52) c-g-l-o-r	
0.320	159.4	0.204	146.2	0.081	32.8
0.362	159.4	0.279	154.9	0.126	47.1
0.405	160.8	0.319	154.4	0.202	63.0
		0.399	144.1	0.279	74.6
45) e-g-j-n-r				0.353	88.4
0.099	71.7	49) c-g-k-o-r		0.420	90.3
0.157	123.8	0.064	41.2		
0.211	126.2	0.100	74.9	53) c-h-j-o-r	
0.230	133.2	0.133	90.1	0.058	56.9
0.257	141.5	0.173	98.2	0.069	79.1
0.328	147.8	0.224	112.9	0.110	104.3
0.397	142.9	0.273	120.1	0.123	119.2
		0.325	125.2	0.144	131.0
46) c-g-j-m-r		0.372	114.4	0.198	133.2
0.063	60.8			0.229	136.7
0.121	111.0	50) c-g-l-n-r		0.308	136.2
0.168	120.9	0.091	36.0		
0.217	130.6	0.132	55.2	54) c-i-j-o-r	
0.262	143.5	0.197	55.5	0.057	111.7
0.314	145.5	0.249	77.1	0.071	219.0
0.362	143.8	0.290	88.8	0.124	255.9
0.386	141.7	0.326	91.1	0.148	268.3
		0.441	90.3	0.244	286.0
47) c-g-j-n-p				0.265	288.0
0.084	86.3	51) c-g-l-n-q		0.291	277.5
0.114	125.1	0.108	49.4		
0.176	137.0	0.147	55.2		
0.224	140.9	0.191	60.2		
0.292	139.8	0.262	72.7		
0.340	142.4	0.302	87.6		
0.390	139.6				

TABLE D.5. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.25 sec and Off-period = 0.25 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
55) a-g-j-o-r		1.120	59.6	63) a-g-l-o-r	
0.552	50.2	1.213	57.1	0.585	23.5
0.648	62.1			0.643	21.9
0.713	64.2	59) a-g-j-n-p		0.775	25.6
0.736	67.3	0.520	40.2	0.883	30.2
0.821	73.3	0.638	58.0	0.930	32.5
0.838	73.4	0.728	61.1	1.013	35.2
0.933	84.2	0.848	62.0	1.083	36.6
0.950	74.1	0.922	61.8	1.202	40.0
1.00	86.9	1.038	60.6	1.273	40.0
1.079	77.8	1.157	58.8		
1.125	85.2			64) b-g-j-o-q	
1.275	78.4	60) a-g-j-m-q		0.142	81.6
		0.520	39.1	0.196	89.0
56) a-g-j-o-q		0.590	59.6	0.267	69.3
0.478	51.3	0.687	71.5	0.300	69.5
0.592	61.6	0.755	75.1	0.388	96.3
0.599	67.8	0.850	76.4	0.502	99.7
0.699	66.3	0.925	73.6	0.622	110.7
0.883	82.4	0.936	69.6	0.782	110.0
0.977	87.0	1.06	66.7		
1.055	84.1	1.16	62.9	65) e-g-j-o-q	
1.157	77.3			0.133	55.0
		61) a-g-k-o-r		0.181	79.9
57) a-g-j-n-q		0.578	39.7	0.293	86.4
0.433	35.2	0.684	39.6	0.345	101.7
0.533	58.6	0.775	45.2	0.445	123.9
0.584	65.7	0.868	48.7	0.559	125.5
0.677	70.2	0.962	51.7	0.627	122.6
0.798	70.6	1.05	59.3		
0.914	69.3	1.12	62.5	66) f-g-j-o-q	
0.962	70.3	1.22	63.2	0.580	53.6
1.126	66.5			0.641	60.8
		62) a-g-l-n-r		0.715	84.0
58) a-g-j-n-r		0.615	21.7	0.766	96.0
0.441	38.6	0.712	22.0	0.823	105.2
0.585	55.8	0.753	27.9	0.893	109.0
0.648	59.0	0.872	27.9	0.915	111.8
0.730	66.8	0.921	28.4	0.984	116.3
0.844	66.0	0.951	30.7	1.069	110.2
0.925	61.0	1.075	34.6	1.170	105.4
1.023	60.2	1.190	36.1		

TABLE D.6. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.25 sec and Off-period = 0.50 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
67) a-g-j-n-q		0.497	64.5	0.764	33.2
0.364	59.4	0.553	73.8	0.860	33.5
0.416	61.0	0.670	74.0		
0.520	68.2	0.812	75.4	72) a-g-l-o-r	
0.557	68.8	0.955	76.3	0.449	21.4
0.614	70.4	1.054	74.6	0.515	22.9
0.679	71.5			0.569	24.1
0.715	71.5	70) a-g-k-o-r		0.617	30.6
0.770	71.3	0.481	37.5	0.626	27.6
0.909	70.6	0.567	43.2	0.767	33.3
		0.634	48.4	0.827	32.1
68) a-g-j-o-q		0.648	48.4	0.895	33.0
0.378	51.8	0.702	50.8		
0.504	69.0	0.774	53.1	73) d-g-j-o-r	
0.616	73.5	0.862	53.2	0.035	52.4
0.700	78.5	0.935	52.9	0.040	62.0
0.812	76.0			0.077	97.1
0.854	73.7	71) a-g-l-n-r		0.121	110.0
0.931	71.2	0.410	21.1	0.195	120.9
		0.506	21.6	0.274	132.3
69) a-g-j-m-q		0.571	28.1	0.329	141.6
0.343	31.0	0.614	28.7	0.372	151.2
0.443	64.1	0.678	31.0	0.463	155.7

TABLE D.7. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.25 sec and Off-period = 0.75 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
74) a-g-j-o-q		76) c-g-j-o-r		0.125	83.5
0.259	44.6	0.079	61.3	0.146	104.4
0.392	60.0	0.116	102.6	0.204	93.5
0.490	71.7	0.162	132.7	0.273	106.9
0.525	74.5	0.216	150.6	0.322	113.1
0.616	76.3	0.291	160.1	0.379	114.8
0.686	70.6	0.361	154.3	0.420	109.9
0.889	65.6	0.416	151.5		
				79) f-g-j-o-r	
75) b-g-j-o-q		77) d-g-j-o-r		0.321	64.4
0.073	48.0	0.026	43.7	0.371	76.2
0.096	71.1	0.061	85.2	0.423	89.7
0.142	91.2	0.108	103.4	0.457	92.3
0.159	91.2	0.138	109.1	0.517	113.9
0.205	93.6	0.218	129.6	0.569	114.8
0.254	95.3	0.269	140.6	0.630	118.3
0.326	98.8	0.320	140.7	0.694	120.1
0.429	101.4				
0.480	103.6	78) e-g-j-o-r			
0.593	105.7	0.092	53.2		

TABLE D.8. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.375 sec and Off-period = 0.375 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
80) a-g-j-o-q		0.679	65.8	1.022	66.0
0.490	50.0	0.812	68.8	1.183	63.2
0.665	64.1	0.945	67.0		

TABLE D.9. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.5 sec and Off-period = 0.5 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
81) c-g-j-o-r		0.159	130.9	0.255	76.2
0.092	65.2	0.219	141.7	0.287	79.2
0.112	103.5	0.297	147.4	0.370	88.4
0.170	155.8	0.391	154.9	0.480	90.3
0.249	164.1	0.472	155.7	0.575	92.2
0.340	169.2	0.583	157.0		
0.427	166.3	0.713	158.4	88) c-g-l-n-r	
0.546	166.9			0.099	33.5
82) c-g-j-n-r		85) c-g-j-n-p		0.138	56.2
0.103	94.1	0.091	82.6	0.243	79.7
0.135	117.8	0.215	137.9	0.293	77.2
0.240	135.5	0.271	143.2	0.385	86.6
0.330	143.3	0.368	149.4	0.513	89.9
0.422	148.9	0.419	153.1	0.594	90.7
0.497	154.5	0.532	153.1		
0.632	150.9	0.634	156.4	89) c-g-l-n-q	
83) c-g-j-m-r		86) c-g-k-o-r		0.099	39.7
0.078	78.2	0.116	87.6	0.168	67.7
0.109	107.8	0.131	98.0	0.256	76.4
0.176	130.0	0.194	109.7	0.352	81.3
0.254	135.7	0.295	124.9	0.444	85.8
0.297	140.8	0.387	130.4	0.511	84.5
0.412	152.6	0.475	128.8	0.612	88.1
0.572	155.5	0.550	129.0		
84) c-g-j-n-q		87) c-g-l-o-r			
0.086	62.9	0.093	35.2		
		0.138	60.2		

TABLE D.10. Data for Pulsed-bed Heat-transfer Coefficients
with On-period = 0.5 sec and Off-period = 1.0 sec

v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)	v_0 , ft/sec	h , Btu/(hr)(°F)(ft ²)
90) d-g-j-o-r		0.130	113.3	0.366	130.4
0.046	82.8	0.205	121.9	0.452	133.7
0.073	99.5	0.281	124.8	0.512	126.2

APPENDIX E

Instantaneous Particle Velocity and Residence Time
in Pulsed Beds

Tables Contained in This Appendix:

<u>No.</u>	<u>Title</u>	<u>Page</u>
E.1.	Particle Velocity and Residence Time with $v_0 = 0.406$ ft/sec at 6 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec	147
E.2.	Particle Velocity and Residence Time with $v_0 = 0.504$ ft/sec at 6 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec	148
E.3.	Particle Velocity and Residence Time with $v_0 = 0.826$ ft/sec at 6 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec	149
E.4.	Particle Velocity and Residence Time with $v_0 = 0.560$ ft/sec at 6 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec.	150
E.5.	Particle Velocity and Residence Time with $v_0 = 0.770$ ft/sec at 6 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec.	151
E.6.	Particle Velocity and Residence Time with $v_0 = 0.987$ ft/sec at 6 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec.	152
E.7.	Particle Velocity and Residence Time with $v_0 = 0.828$ ft/sec at 1.5 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec.	154
E.8.	Particle Velocity and Residence Time with $v_0 = 0.915$ ft/sec at 1.5 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec	154

TABLE E.1. Particle Velocity and Residence Time with $v_0 = 0.406$ ft/sec
at 6 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.005	0.0105	0.365	0.170	0.0293	0.109
0.010	0.106	0.351	0.175	-0.103	0.100
0.015	0.139	0.342	0.180	-0.179	0.102
0.020	0.240	0.286	0.185	-0.320	0.106
0.025	0.267	0.247	0.190	-0.403	0.102
0.030	0.358	0.237	0.195	-0.522	0.109
0.035	0.389	0.203	0.200	-0.790	0.106
0.040	0.475	0.167	0.205	-0.264	0.107
0.045	0.499	0.160	0.210	-0.576	0.109
0.050	0.530	0.141	0.215	-0.595	0.105
0.055	0.536	0.142	0.220	-0.592	0.102
0.060	0.552	0.133	0.225	-0.630	0.176
0.065	0.578	0.125	0.230	-0.596	0.203
0.070	0.597	0.115	0.235	-0.561	0.194
0.075	0.621	0.105	0.240	-0.572	0.228
0.080	0.612	0.096	0.245	-0.472	0.242
0.085	0.631	0.086	0.250	-0.442	0.239
0.090	0.615	0.096	0.255	-0.451	0.270
0.095	0.658	0.094	0.260	-0.412	0.265
0.100	0.566	0.101	0.265	-0.544	0.296
0.105	0.598	0.108	0.270	-0.327	0.291
0.110	0.576	0.113	0.275	-0.440	0.320
0.115	0.510	0.111	0.280	-0.3796	0.315
0.120	0.675	0.116	0.285	-0.2966	0.345
0.125	0.400	0.123	0.290	-0.230	0.340
0.130	0.555	0.117	0.295	-0.0987	0.337
0.135	0.712	0.120	0.300	-0.01659	0.371
0.140	0.577	0.121	0.305	0	
0.145	0.556	0.114	.	.	.
0.150	0.482	0.115	.	.	.
0.155	0.356	0.109	.	.	.
0.160	0.259	0.113	0.535	0	0.371
0.165	0.118	0.110			

TABLE E.2. Particle Velocity and Residence Time with $v_0 = 0.504$ ft/sec
at 6 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.005	0.112	0.390	0.275	-0.559	0.051
0.010	0.201	0.380	0.280	-0.502	0.049
0.015	0.293	0.368	0.285	-0.521	0.049
0.020	0.369	0.356	0.290	-0.496	0.049
0.025	0.441	0.342	0.295	-0.441	0.051
0.030	0.551	0.330	0.300	-0.383	0.061
0.035	0.616	0.320	0.305	-0.349	0.068
0.040	0.636	0.207	0.310	-0.333	0.074
0.045	0.698	0.338	0.315	-0.362	0.088
0.050	0.816	0.328	0.320	-0.292	0.092
0.055	0.841	0.318	0.325	-0.211	0.095
0.060	0.895	0.308	0.330	-0.188	0.098
0.065	0.925	0.298	0.335	-0.117	0.100
0.070	0.959	0.288	0.340	-0.0491	0.094
0.075	0.993	0.258	0.345	0	0.098
0.080	1.02	0.238	0.350		0.095
0.085	1.06		0.355		0.093
0.090	1.10		0.360		0.087
0.095	1.09		0.365		0.088
0.100	1.07		0.370		0.092
0.105	1.03		0.375		0.090
0.110	1.01		0.380		0.093
0.115	0.991		0.385		0.091
0.120	0.990		0.390		0.089
0.125	0.912		0.395		0.085
0.130	0.905		0.400		0.088
0.135	0.860		0.405		0.085
0.140	0.756		0.410		0.079
0.145	0.627		0.415		0.073
0.150	0.460		0.420		0.063
0.155	0.297		0.425		0.060
0.160	0.172		0.430		0.061
0.165	0.0267		0.435		0.061
0.170	-0.124		0.440		0.064
0.175	-0.231		0.445		0.066
0.180	-0.384		0.450		0.133
0.185	-0.415		0.455		0.157
0.190	-0.500	0.238	0.460		0.201
0.195	-0.515	0.242	0.465		0.244
0.200	-0.628	0.242	0.470		0.243
0.205	-0.663	0.223	0.475		0.283
0.210	-0.658	0.225	0.480		0.325
0.215	-0.710	0.226	0.485		0.322
0.220	-0.757	0.209	0.490		0.364
0.225	-0.697	0.193	0.495		0.360
0.230	-0.699	0.193	0.500		0.401
0.235	-0.666	0.176	0.505		0.395
0.240	-0.718	0.156	0.510		
0.245	-0.724	0.137	0.515		
0.250	-0.744	0.116	0.520		
0.255	-0.691	0.095	0.525		
0.260	-0.689	0.074	0.530		
0.265	-0.599	0.053	0.535	0	
0.270	-0.556	0.052			

TABLE E.3. Particle Velocity and Residence Time with $v_0 = 0.826$ ft/sec
at 6 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.005	0.0130	0.057	0.275	-0.543	0.074
0.010	0.0926	0.057	0.280	-0.553	0.075
0.015	0.191	0.057	0.285	-0.548	0.075
0.020	0.247	0.056	0.290	-0.541	0.075
0.025	0.411	0.051	0.295	-0.528	0.075
0.030	0.502	0.052	0.300	-0.501	0.076
0.035	0.655	0.053	0.305	-0.521	0.076
0.040	0.760	0.053	0.310	-0.519	0.076
0.045	0.929	0.052	0.315	-0.489	0.076
0.050	1.05	0.050	0.320	-0.539	0.075
0.055	1.27	0.048	0.325	-0.522	
0.060	1.32	0.044	0.330	-0.532	
0.065	1.43	0.039	0.335	-0.516	
0.070	1.49	0.037	0.340	-0.548	
0.075	1.51	0.036	0.345	-0.520	0.075
0.080	1.58	0.035	0.350	-0.563	0.074
0.085	1.56	0.034	0.355	-0.583	0.074
0.090	1.56		0.360	-0.479	0.073
0.095	1.63		0.365	-0.514	0.073
0.100	1.58		0.370	-0.530	0.072
0.105	1.66		0.375	-0.546	
0.110	1.57		0.380	-0.523	
0.115	1.58	0.034	0.385	-0.554	
0.120	1.68	0.035	0.390	-0.554	
0.125	1.65	0.047	0.395	-0.590	0.072
0.130	1.63	0.064	0.400	-0.593	0.073
0.135	1.62	0.078	0.405	-0.577	0.073
0.140	1.62	0.083	0.410	-0.561	0.074
0.145	1.62	0.095	0.415	-0.594	
0.150	1.52	0.097	0.420	-0.544	
0.155	1.32	0.090	0.425	-0.511	
0.160	1.10	0.096	0.430	-0.541	
0.165	0.890	0.092	0.435	-0.514	0.074
0.170	0.670	0.086	0.440	-0.533	0.075
0.175	0.418	0.086	0.445	-0.463	0.075
0.180	0.258	0.087	0.450	-0.527	0.075
0.185	0.105	0.091	0.455	-0.572	0.076
0.190	-0.00732	0.088	0.460	-0.571	0.082
0.195	-0.115	0.092	0.465	-0.601	0.087
0.200	-0.195	0.088	0.470	-0.573	0.094
0.205	-0.314	0.093	0.475	-0.545	0.098
0.210	-0.350	0.090	0.480	-0.554	0.096
0.215	-0.442	0.089	0.485	-0.515	0.102
0.220	-0.494	0.085	0.490	-0.554	0.098
0.225	-0.595	0.082	0.495	-0.495	0.101
0.230	-0.608	0.084	0.500	-0.460	0.104
0.235	-0.665	0.080	0.505	-0.435	0.100
0.240	-0.638	0.070	0.510	-0.411	0.102
0.245	-0.636	0.069	0.515	-0.339	0.099
0.250	-0.638	0.071	0.520	-0.309	0.101
0.255	-0.665	0.071	0.525	-0.222	0.098
0.260	-0.631	0.072	0.530	-0.139	0.096
0.265	-0.615	0.073	0.535	-0.0468	0.095
0.270	-0.539	0.073			

TABLE E.4. Particle Velocity and Residence Time with $v_0 = 0.560$ ft/sec
at 6 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.005	0.0356	0.323	0.205	0.170	0.221
0.010	0.0622	0.325	0.210	0.161	0.217
0.015	0.104	0.325	0.215	0.158	0.212
0.020	0.105	0.328	0.220	0.120	0.219
0.025	0.0931	0.328	0.225	0.127	0.215
0.030	0.158	0.339	0.230	0.130	0.212
0.035	0.0883	0.343	0.235	0.135	0.206
0.040	0.166	0.319	0.240	0.132	0.201
0.045	0.203	0.303	0.245	0.0688	0.198
0.050	0.209	0.304	0.250	0.00276	0.197
0.055	0.198	0.307	0.255	-0.0415	0.175
0.060	0.195	0.320	0.260	-0.0858	0.177
0.065	0.187	0.283	0.265	-0.117	0.181
0.070	0.241	0.282	0.270	-0.214	0.186
0.075	0.0903	0.288	0.275	-0.263	0.195
0.080	0.347	0.294	0.280	-0.371	0.180
0.085	0.219	0.260	0.285	-0.402	0.190
0.090	0.212	0.262	0.290	-0.467	0.176
0.095	0.220	0.272	0.295	-0.426	0.185
0.100	0.222	0.236	0.300	-0.504	0.171
0.105	0.208	0.236	0.305	-0.510	0.234
0.110	0.218	0.247	0.310	-0.536	0.235
0.115	0.197	0.229	0.315	-0.563	0.253
0.120	0.232	0.228	0.320	-0.587	0.231
0.125	0.268	0.227	0.325	-0.566	0.265
0.130	0.201	0.236	0.330	-0.573	0.275
0.135	0.226	0.235	0.335	-0.582	0.283
0.140	0.193	0.234	0.340	-0.639	0.246
0.145	0.195	0.231	0.345	-0.635	0.270
0.150	0.262	0.231	0.350	-0.606	0.294
0.155	0.221	0.238	0.355	-0.446	0.278
0.160	0.279	0.235	0.360	-0.308	0.304
0.165	0.234	0.230	0.365	-0.103	0.296
0.170	0.186	0.239	0.370	0.0975	0.333
0.175	0.191	0.236	0.375	0	0.336
0.180	0.195	0.232	.	.	.
0.185	0.207	0.227	.	.	.
0.190	0.188	0.224	.	.	.
0.195	0.167	0.230	0.520	0	0.336
0.200	0.168	0.225			

TABLE E.5. Particle Velocity and Residence Time with $v_0 = 0.770$ ft/sec
at 6 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.005	0.0575	0.212	0.230	0.532	0.118
0.010	0.0506	0.201	0.235	0.542	0.121
0.015	0.158	0.196	0.240	0.548	0.124
0.020	0.176	0.168	0.245	0.545	0.117
0.025	0.168	0.163	0.250	0.461	0.119
0.030	0.358	0.160	0.255	0.299	0.122
0.035	0.126	0.155	0.260	0.275	0.117
0.040	0.614	0.154	0.265	0.165	0.112
0.045	0.425	0.148	0.270	0.0322	0.110
0.050	0.438	0.145	0.275	-0.0578	0.102
0.055	0.338	0.143	0.280	-0.168	0.103
0.060	0.629	0.139	0.285	-0.274	0.108
0.065	0.491	0.133	0.290	-0.539	0.105
0.070	0.542	0.129	0.295	-0.246	0.110
0.075	0.573	0.124	0.300	-0.519	0.105
0.080	0.550	0.120	0.305	-0.552	0.110
0.085	0.456	0.115	0.310	-0.578	0.107
0.090	0.522	0.110	0.315	-0.596	0.102
0.095	0.604	0.105	0.320	-0.605	0.106
0.100	0.557	0.098	0.325	-0.654	0.100
0.105	0.541	0.092	0.330	-0.649	0.094
0.110	0.550	0.092	0.335	-0.662	0.187
0.115	0.577	0.088	0.340	-0.623	0.079
0.120	0.580	0.087	0.345	-0.631	0.079
0.125	0.530	0.087	0.350	-0.530	0.070
0.130	0.594	0.086	0.355	-0.620	0.070
0.135	0.688	0.085	0.360	-0.565	0.091
0.140	0.548	0.084	0.365	-0.533	0.090
0.145	0.623	0.085	0.370	-0.484	0.109
0.150	0.582		0.375	-0.597	0.108
0.155	0.581		0.380	-0.556	0.125
0.160	0.555		0.385	-0.561	0.141
0.165	0.557	0.085	0.390	-0.621	0.138
0.170	0.607	0.084	0.395	-0.851	0.150
0.175	0.575	0.084	0.400	-0.597	0.164
0.180	0.621	0.084	0.405	-0.421	0.179
0.185	0.577	0.086	0.410	-0.627	0.173
0.190	0.541	0.095	0.415	-0.582	0.184
0.195	0.570	0.103	0.420	-0.344	0.197
0.200	0.573	0.102	0.425	-1.75	0.193
0.205	0.564	0.109	0.430	0	0.211
0.210	0.587	0.116			
0.215	0.551	0.113			
0.220	0.542	0.118			
0.225	0.559	0.122	0.515	0	0.211

TABLE E.6. Particle Velocity and Residence Time with $v_0 = 0.987$ ft/sec
at 6 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.005	0.0901	0.091	0.265	0.164	0.120
0.010	0.172	0.092	0.270	0.0831	0.117
0.015	0.161	0.095	0.275	-0.0330	0.109
0.020	0.162	0.096	0.280	-0.0792	0.110
0.025	0.193	0.100	0.285	-0.149	0.111
0.030	0.341	0.100	0.290	-0.152	0.115
0.035	0.114	0.105	0.295	-0.292	0.118
0.040	0.268	0.105	0.300	-0.305	0.113
0.045	0.273	0.108	0.305	-0.370	0.118
0.050	0.244	0.109	0.310	-0.404	0.113
0.055	0.338	0.110	0.315	-0.445	0.118
0.060	0.308	0.114	0.320	-0.464	0.113
0.065	0.334	0.114	0.325	-0.472	0.117
0.070	0.341	0.115	0.330	-0.470	0.112
0.075	0.393	0.116	0.335	-0.496	0.116
0.080	0.364	0.117	0.340	-0.458	0.109
0.085	0.356	0.120	0.345	-0.531	0.104
0.090	0.372	0.119	0.350	-0.527	0.105
0.095	0.392	0.120	0.355	-0.491	0.098
0.100	0.406	0.129	0.360	-0.531	0.098
0.105	0.379	0.120	0.365	-0.480	0.081
0.110	0.409	0.119	0.370	-0.484	0.079
0.115	0.433	0.119	0.375	-0.525	0.078
0.120	0.391	0.117	0.380	-0.555	0.076
0.125	0.402	0.117	0.385	-0.531	0.076
0.130	0.435	0.113	0.390	-0.553	0.075
0.135	0.464	0.111	0.395	-0.516	0.074
0.140	0.437	0.110	0.400	-0.575	0.072
0.145	0.489	0.105	0.405	-0.561	0.072
0.150	0.444	0.103	0.410	-0.198	0.074
0.155	0.482	0.101	0.415	-0.756	0.068
0.160	0.339	0.100	0.420	-0.622	0.068
0.165	0.620	0.096	0.425	-0.617	0.066
0.170	0.507	0.095	0.430	-0.680	0.064
0.175	0.537	0.091	0.435	-0.685	0.064
0.180	0.579	0.084	0.440	-0.707	0.061
0.185	0.581	0.088	0.445	-0.690	0.060
0.190	0.620	0.084	0.450	-0.642	0.059
0.195	0.608	0.084	0.455	-0.695	0.058
0.200	0.638	0.093	0.460	-0.725	0.057
0.205	0.632	0.092	0.465	-0.725	0.057
0.210	0.592	0.099	0.470	-0.870	0.053
0.215	0.927	0.104	0.475	-0.810	0.054
0.220	0.432	0.114	0.480	-0.885	0.051
0.225	0.736	0.120	0.485	-0.872	0.051
0.230	0.725	0.114	0.490	-0.780	0.053
0.235	0.728	0.119	0.495	-0.730	0.053
0.240	0.714	0.121	0.500	-0.764	0.052
0.245	0.630	0.124	0.505	-0.792	0.052
0.250	0.522	0.127	0.510	-0.838	0.050
0.255	0.385	0.121	0.515	-0.837	0.048
0.260	0.293	0.120	0.520	-0.869	0.046

TABLE E.6 (Contd.)

Time, sec	U_p , ft/sec	τ , sec	Time, sec	U_p , ft/sec	τ , sec
0.525	-0.949	0.043	0.780	0.310	0.114
0.530	-1.08	0.041	0.785	0.194	0.120
0.535	-1.16	0.040	0.790	0.0828	0.113
0.540	-1.18	0.037	0.795	0.00455	0.113
0.545	-1.16	0.037	0.800	-0.0927	0.107
0.550	-1.18	0.037	0.805	-0.125	0.109
0.555	-1.23	0.035	0.810	-0.195	0.113
0.560	-1.23	0.043	0.815	-0.269	0.113
0.565	-1.33	0.052	0.820	-0.308	0.111
0.570	-1.27	0.060	0.825	-0.391	0.113
0.575	-1.11	0.061	0.830	-0.391	0.113
0.580	-0.809	0.067	0.835	-0.443	0.113
0.585	-0.407	0.069	0.840	-0.484	0.111
0.590	-0.273	0.067	0.845	-0.450	0.113
0.595	0.0619	0.072	0.850	-0.534	0.108
0.600	0.241	0.073	0.855	-0.530	0.103
0.605	0.508	0.072	0.860	-0.504	0.106
0.610	0.719	0.076	0.865	-0.532	0.100
0.615	0.784	0.077	0.870	-0.544	0.100
0.620	0.877	0.076	0.875	-0.566	0.093
0.625	0.910	0.075	0.880	-0.568	0.085
0.630	0.930	0.073	0.885	-0.519	0.076
0.635	0.941	0.066	0.890	-0.561	0.074
0.640	0.961	0.064	0.895	-0.515	0.074
0.645	0.891	0.062	0.900	-0.528	0.073
0.650	0.834	0.059	0.905	-0.575	0.072
0.655	0.835	0.059	0.910	-0.585	0.071
0.660	0.866	0.058	0.915	-0.583	0.070
0.665	0.768	0.061	0.920	-0.496	0.071
0.670	0.806	0.062	0.925	-0.655	0.070
0.675	0.789	0.063	0.930	-0.586	0.069
0.680	1.08	0.059	0.935	-0.568	0.068
0.685	0.510	0.064	0.940	-0.551	0.068
0.690	0.847	0.063	0.945	-0.583	0.067
0.695	0.792	0.064	0.950	-0.607	0.067
0.700	0.772		0.955	-0.604	0.067
0.705	0.798		0.960	-0.652	0.065
0.710	0.783		0.965	-0.590	0.066
0.715	0.796	0.064	0.970	-0.628	0.093
0.720	0.764	0.065	0.975	-0.664	0.104
0.725	0.748	0.077	0.980	-0.621	0.102
0.730	0.861	0.076	0.985	-0.704	0.110
0.735	0.833	0.086	0.990	-0.703	0.118
0.740	0.781	0.095	0.995	-0.686	0.126
0.745	0.835	0.102	1.000	-0.706	0.132
0.750	0.705	0.108	1.005	-0.675	0.122
0.755	0.876	0.112	1.010	-0.565	0.127
0.760	0.760	0.116	1.015	-0.313	0.133
0.765	0.612	0.118	1.020	-0.159	0.128
0.770	0.291	0.124	1.025	-0.0482	0.125
0.775	0.453	0.117	1.030	0	0.139

TABLE E.7. Particle Velocity and Residence Time with $v_0 = 0.828$ ft/sec at
1.5 in., $t_{on} = 0.125$ sec, and $t_{off} = 0.375$ sec

Time, sec	U_p , ft/sec	Time, sec	U_p , ft/sec	Time, sec	U_p , ft/sec
0.005	0.0387	0.330	0	0.580	1.62
0.010	0.109	0.335	-1.33	0.585	1.52
0.015	0.292	0.340	-1.30	0.590	1.25
0.020	0.394	0.345	-0.921	0.595	1.75
0.025	0.542	0.350	-0.676	0.600	1.80
0.030	0.654	0.355	-0.280	0.605	1.68
0.035	0.862	0.360	-0.156	0.610	Gas Void
0.040	1.00	0.365	-0.0623		
0.045	1.09	0.370	0.133		
0.050	1.18	0.375	0		
0.055	1.25			0.840	Gas Void
0.060	1.36			0.845	0
0.065	1.44			0.850	-1.33
0.070	1.44	0.515	0	0.855	-0.572
0.075	1.53	0.520	0.103	0.860	-0.722
0.080	1.57	0.525	0.298	0.865	-0.468
0.085	1.62	0.530	0.417	0.870	-0.277
0.090	1.78	0.535	0.622	0.875	-0.108
0.095	1.67	0.540	0.733	0.880	-0.0436
0.100	1.64	0.545	0.903	0.885	-0.00492
0.105	1.45	0.550	1.12	0.890	0
0.110	Gas Void	0.555	1.21		
		0.560	1.36		
		0.565	1.45		
		0.570	1.55	1.025	0
0.325	Gas Void	0.575	1.61		

TABLE E.8 Particle Velocity and Residence Time with $v_0 = 0.915$ ft/sec at
1.5 in., $t_{on} = 0.25$ sec, and $t_{off} = 0.25$ sec

Time, sec	U_p , ft/sec	Time, sec	U_p , ft/sec	Time, sec	U_p , ft/sec
0.005	0.0433	0.440	0	0.580	0.542
0.010	0.131	0.445	-0.875	0.585	0.564
0.015	0.210	0.450	-0.948	0.590	0.601
0.020	0.270	0.455	-0.410	0.595	0.622
0.025	0.312	0.460	-0.259	0.600	0.681
0.030	0.375	0.465	-0.153	0.605	0.617
0.035	0.472	0.470	-0.0642	0.610	0.648
0.040	0.471	0.475	-0.0225	0.615	0.699
0.045	0.504	0.480	-0.00663	0.620	0.821
0.050	0.637	0.485	0	0.625	0.695
0.055	0.555	0.490	0	0.630	0.739
0.060	0.593	0.495	0	0.635	0.763
0.065	0.609	0.500	0	0.640	0.755
0.070	0.664	0.505	0	0.645	0.793
0.075	0.663	0.510	-0.000798	0.650	0.783
0.080	0.664	0.515	0.109	0.655	0.803
0.085	0.704	0.520	0.115	0.660	0.818
0.090	0.739	0.525	0.216	0.665	Gas Void
0.095	0.854	0.530	0.553		
0.100	0.728	0.535	-0.0286		
0.105	0.796	0.540	0.303		
0.110	0.850	0.545	0.345	0.955	Gas Void
0.115	0.859	0.550	0.351	0.960	0
0.120	Gas Void	0.555	0.375		
		0.560	0.420		
		0.565	0.420		
		0.570	0.524	1.030	0
0.435	Gas Void	0.575	0.532		

ACKNOWLEDGMENTS

I wish to express my appreciation to Professor William T. Brazelton for his guidance and suggestions in conducting this work.

I also wish to express my appreciation to Dr. D. Ramaswami, who supervised this investigation at Argonne National Laboratory, and to Mr. A. A. Jonke for his continued interest in this investigation. Dr. J. D. Gabor gave valuable advice to the author.

I am grateful to Dr. Robert A. Brusenback for lending his films and his equipment.

REFERENCES

1. Massimilla, L., Volpicelli, G., and Raso, G., Chem. Eng. Progr. Symp. Ser. No. 62, 63 (1966).
2. Berg, D. B., and Miniscalco, B., Chem. Process. (Chicago) 31(4), 30-31 (April 1968).
3. Bokun, I. A., and Zabrodskii, S. S., "Experimental Study of Heat Transfer between a Pulsating Bed and the Heating Surface," in *Investigation of Heat and Mass Transfer in Technological Processes and Apparatus*, A. V. Lykov, ed., Nauka i Tekhnika, Minsk (1966), pp. 27-32; Trans: ANL-Trans-592 (March 1968).
4. Zabrodskii, S. S., and Bokun, I. A., "Heat Transfer between a Pulsating Bed of Moist Tetracycline and the Heating Surface," in *Investigation of Heat and Mass Transfer in Technological Processes and Apparatus*, A. V. Lykov, ed., Nauka i Tekhnika, Minsk (1966), pp. 135-139; Trans: ANL-Trans-593 (1968).
5. Belik, L., Chem. Ing. Tech. 32, 253-277 (1960); Trans: ANL-Trans-613 (March 1968).
6. Levey, R. P., Jr., U.S. Patent 3164440 (Jan. 5, 1965).
7. Heidt, H. M., Levey, R. P., Jr., and Hamrin, C. E., Chem. Eng. Progr. Symp. Ser. 65, 43-41 (1966).
8. Krasuk, J. H., and Smith, J. M., AIChE J 10, 759-763 (1964).
9. Hogg, G. W., and Grimmet, E. S., Chem. Eng. Progr., Symp. Ser. 62, 51-66 (1966).
10. Mickley, H. S., and Trilling, C. A., Ind. Chem. Eng. 41, 1135-1147 (1949).
11. Levenspiel, O., and Walton, J. S., Chem. Eng. Progr. Symp. Ser. 50, 1-13 (1954).
12. Mickley, H. S., and Fairbanks, D. F., AIChE J 1, 374-384 (1955).
13. Jacob, A., and Osberg, G. L., Can. J. Chem. Eng. 35, 5 (1957).
14. Ernst, R., Chem. Ingr. Tech. 31, 166-173 (1959).
15. Zabrodskii, S. S., "International Developments in Heat Transfer," *ASME-AIChE Intl. Heat Trans. Conference*, pp. 737-741 (1961).
16. Zabrodskii, S. S., *Hydrodynamics and Heat Transfer in Fluidized Bed*, pp. 226-243, MIT Press, Cambridge (1963).
17. Mickley, H. S., Fairbanks, D. F., and Hawthorn, R. D., Chem. Eng. Progr. Symp. Ser. 57, 51-60 (1961).
18. Brusenback, R. A., Ph.D. dissertation, Northwestern University (1963).
19. Botterill, J. S. M., and Williams, J. R., Trans. Inst. Chem. Eng. 41, 217-230 (1963).
20. Baskakov, A. P., Intern. Chem. Eng. 4, 320-324 (1964).
21. Ziegler, E. N., Koppel, L. B., and Brazelton, W. T., Ind. Eng. Chem. Fundam. 3, 324-328 (1964).

22. Wasmund, B., and Smith, J. W., Can. J. Chem. Eng., 246-251 (Oct 1965).
23. Botterill, J. S. M., Brundrett, G. W., Cain, G. L., and Elliott, D. E., Chem. Eng. Progr. Symp. Ser. 62, 1-6 (1966).
24. Botterill, J. S. M., Butt, M. H. D., Cain, G. L., and Redish, K. L., in *Proceedings of the International Symposium of Fluidization*, Eindhoven, pp. 442-457 (1967).
25. Botterill, J. S. M., Butt, M. H. D., Cain, G. L., Chandrasekher, R., and Williams, J. R., *Proceedings of the International Symposium of Fluidization*, 458-467 (1967).
26. Couderc, J. P., Angelino, H., and Enjalbert, M., Chem. Eng. Sci. 22, 99-107 (1967).
27. Couderc, J. P., Angelino, H., and Enjalbert, M., Chem. Eng. Sci. 22, 109-118 (1967).
28. Patel, R. D., Ph.D. dissertation, Purdue University (1967).
29. Koppel, L. B., Patel, R. D., and Holmes, J. T., AIChE J 12, 941-946 (1966).
30. Koppel, L. B., Patel, R. D., and Holmes, J. T., AIChE J 12, 947-955 (1966).
31. Davidson, J. F., and Harrison, D., *Fluidization Particles*, Cambridge University Press (1963).
32. Orniston, R. M., Mitchell, F. R. G., and Davidson, J. F., Trans. Inst. Chem. Engrs. (London) 43, T-209 (1965).
33. Davidson, J. F., and Harrison, D., Chem. Eng. Sci. 21, 731-738 (1966).
34. Swift, D. L., Intern. J. Mass Heat Transfer 9, 1061-1074 (1966).
35. Baerns, M., Ind. Eng. Chem. Fundam. 5, 508-516 (1966).
36. Gel'perin, N. I., Ainstein, V. G., and Romanova, N. A., Intern. Chem. Eng. 4, 502-506 (1964).
37. Gabor, J. D., Proc. Intern. Symp. on Fluidization, 230-242 (1967).
38. Toei, R., Matsuno, R., and Nagai, Y., Chem. Eng. Japan 31, 457-462 (1967).