135
70

MASS TRANSFER IN AERATED VIBRATED BEDS

by

Christian E. Raison

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Chemical Engineering

APPROVED:

Dr. Arthur M. Squires, Chairman

Dr. George B. Wills

Dr. J. Robert Mahan

Dr. Benku Thomas

February, 1990

Blacksburg, Virginia

MASS TRANSFER IN AERATED VIBRATED BEDS

by

Christian E. Raison

Dr. Arthur M. Squires, Chairman

Chemical Engineering

(ABSTRACT)

A vibrated bed is a mobile layer of solid particles contained in a vessel that is vertically vibrated. When a flow of gas is maintained through it , the bed is called an aerated vibrated bed and a vibrated gas-fluidized bed if the gas stream is greater than the minimum fluidization velocity of the particles.

Mass transfer rates from solid particles coated with naphthalene to a nitrogen stream, the fluidizing gas, are determined using a gas chromatographic technique.
Two kinds of coated beads of different densities are used: Master Beads and low-density glass beads. The investigation is done using a cylindrical vessel with bed depths of 24 mm, 12.7 mm, and 1 mm (ultra-shallow bed). A range of solid particles from 125 to 841 microns of geometric mean size is employed. Using a vibrational frequency of 25 Hz, the particle bed is vibrated at different intensities up to four times the gravitational acceleration.

Vibrations increase the mass transfer rate to some extent depending on the bed depth. The mass transfer process is more important in shallow beds, where strong solid mixing occurs, than in deeper beds, where bulk-circulation patterns affect the naphthalene sublimation. Higher mass transfer rates are obtained with larger as well as heavier particles.

Acknowledgements

I would like to express my appreciation to my thesis advisor, Dr. Arthur M. Squires, for giving me the opportunity to work in his research group.

I would also like to thank Dr. Georges B. Wills and Dr. J. Robert Mahan for serving in my committee.

I am deeply indebted to Dr. Benku Thomas for his guidance and helpful suggestions.

I am grateful to DU PONT DE NEMOURS for their support of this project.

I am thankful to Mme Nicole Jaffrin and Dr. J. Robert Mahan, coordinators of the exchange program between Virginia Polytechnic and State University and the Université de Technologie de Compiègne, for provinding me the opportunity to study at VPI&SU.

I would like to thank all my friends who helped me in many ways during this project, especially Mark Mason, Greg Benge, and Riley Chan for their constant support during this work.

Thanks to my friends Sylvie Hamon, Cathy Guigou, Pascale Marin-Laflèche, Frederic Rivet, Pancho, and Rémi for the many enjoyable moments spent at Blacksburg.

Finally, I would like to express a special thanks to my family for their support and encouragement throughout my studies.

Table of Contents

1.0 Introduction 1
1.1 Review of Fluidization 2
1.2 Background on Vibrated Beds 6
1.3 Mass Transfer in Fluidized Beds 7
1.4 Mechanics of Vibrated Beds 15
1.5 Scope of This Study 19

2.0 Experimental Work 20
2.1 Apparatus 20
2.2 Particle Types, Sizes, and Densities 25
2.3 Mass Transfer Theory 28
2.4 Calibration of the Gas Chromatograph 30
2.4.1 Experimental System 30
2.4.2 Experimental Procedure and Results 33

3.0 Mass Transfer Experiments. Results and Discussion 36
3.1 Experimental Procedure 36

3.2 Effect of Vibration Intensity 38
3.3 Effect of Particle Size and Density 48
3.4 Effect of Bed Height 53

4.0 Conclusion **61**

5.0 Bibliography **63**

Appendix A. Tyler Standard Designation **65**

Appendix B. Gas Chromatograph Calibration **66**

Appendix C. Experimental Results **69**

Appendix D. Minimum Fluidization Velocity **116**

Vita **125**

List of Illustrations

Figure 1. Various kinds of contacting of a batch of solids by gas 4
Figure 2. Pressure drop versus gas velocity for a sand particles bed 5
Figure 3. Experimental mass transfer in gas fluidized systems. 11
Figure 4. Experimental results with mechanical mixing 12
Figure 5. Effect of bed diameter on mass rates in fluidized beds 14
Figure 6. Effect of bed height on mass rates in fluidized beds 16
Figure 7. The bouncing motion of a vibrated bed 18
Figure 8. Schematic drawing of the equipment. 22
Figure 9. Aerated Vibrated Bed 24
Figure 10. Naphthalene saturator 32
Figure 11. Gas chromatograms 34
Figure 12. Gas chromatograph calibration 35
Figure 13. Effect of vibration intensity on small particles 39
Figure 14. Effect of vibration intensity on big particles 40
Figure 15. Effect of vibration intensity on small, low density glass beads 42
Figure 16. Mass transfer results at K = 0 (bed depth 24 mm). 43
Figure 17. Mass transfer results at K = 2 (bed depth 24 mm) 44
Figure 18. Mass transfer results at K = 4 (bed depth 24 mm) 45
Figure 19. Mass transfer results at K = 0, (bed depth 24 mm) 46

Figure 20. Mass transfer results at K = 0, (bed depth 1 mm) 47
Figure 21. Effect of particle size and density; K = 2, bed depth = 24 mm 49
Figure 22. Effect of particle size and density; K = 2, bed depth = 1 mm. 50
Figure 23. Effect of particle size and density; K = 4, bed depth = 24 mm. 51
Figure 24. Effect of particle size and density; K = 4, bed depth = 1 mm. 52
Figure 25. Effect of bed height; -16 + 30 Master Beads, K = 4 and 2. 54
Figure 26. Effect of bed height; -40 + 50 Master Beads, K = 4 and 2. 55
Figure 27. Effect of bed height; -60 + 70 low density glass beads, K = 4 and 2. 56
Figure 28. -16 + 30 low density glass beads; bed depth = 1 mm 58
Figure 29. Effect of bed height on mass transfer at K = 0. 59
Figure 30. -16 + 30 Master Beads; bed depth = 24 mm. 74
Figure 31. -16 + 30 Master Beads; bed depth = 1 mm. 78
Figure 32. -16 + 30 Low density glass beads; bed depth = 24 mm. 82
Figure 33. -16 + 30 Low density glass beads; bed depth = 1 mm. 86
Figure 34. -40 + 50 Master Beads; bed depth = 24 mm. 90
Figure 35. -40 + 50 Master Beads; bed depth = 1 mm. 93
Figure 36. -60 + 70 Master Beads; bed depth = 1 mm. 98
Figure 37. -60 + 70 Low density glass beads; bed depth = 24 mm. 102
Figure 38. -60 + 70 Low density glass beads; bed depth = 1 mm. 106
Figure 39. -100 + 140 Master Beads; bed depth = 1 mm. 110
Figure 40. -100 + 140 Low density glass beads; bed depth = 1 mm. 114
Figure 41. Pressure drop across grid plate. 118
Figure 42. Minimum fluidization velocity; -16 + 30 glass beads. 119
Figure 43. Minimum fluidization velocity; -40 + 50 Master Beads. 120
Figure 44. Minimum fluidization velocity; -60 + 70 Master Beads. 121
Figure 45. Minimum fluidization velocity; -60 + 70 glass beads. 122

Figure 46. Minimum fluidization velocity; -100+140 Master Beads. 123
Figure 47. Minimum fluidization velocity; -100+140 glass beads. 124

List of Tables

Table 1. Experimental conditions used in previous mass transfer studies. 10

Table 2. Size ranges and densities of coated beads. 27

Table 3. Tyler Standard Designation. 65

Table 4. Vapor pressure of naphthalene. 67

Table 5. Gas Chromatograph calibration 68

Table 6. -16+30 Master Beads; K=4, bed depth=24 mm. 71

Table 7. -16+30 Master Beads; K=2, bed depth=24 mm. 72

Table 8. -16+30 Master Beads; K=0, bed depth=24 mm. 73

Table 9. -16+30 Master Beads; K=4, bed depth=1 mm. 75

Table 10. -16+30 Master Beads; K=2, bed depth=1 mm. 76

Table 11. -16+30 Master Beads; K=0, bed depth=1 mm. 77

Table 12. -16+30 Low density glass beads; K=4, depth=24 mm. 79

Table 13. -16+30 Low density glass beads; K=2, bed depth=24 mm. 80

Table 14. -16+30 Low density glass beads; K=0, bed depth=24 mm. 81

Table 15. -16+30 Low density glass beads; K=4, depth=1 mm. 83

Table 16. -16+30 Low density glass beads; K=2, bed depth=1 mm. 84

Table 17. -16+30 Low density glass beads; K=0, bed depth=1 mm. 85

Table 18. -40+50 Master Beads; K=4, bed depth=24 mm. 87

Table 19. -40+50 Master Beads; K=2, bed depth=24 mm. 88

Table 20. -40+50 Master Beads; K=0, bed depth=24 mm. 89
Table 21. -40+50 Master Beads; K=4, bed depth=1 mm. 91
Table 22. -40+50 Master Beads; K=0, bed depth=1 mm. 92
Table 23. -40+50 Master Beads; K=0, bed depth=12.7 mm. 94
Table 24. -60+70 Master Beads; K=4, bed depth=1 mm. 95
Table 25. -60+70 Master Beads; K=2, bed depth=1 mm. 96
Table 26. -60+70 Master Beads; K=0, bed depth=1 mm. 97
Table 27. -60+70 Low density glass beads; K=4, depth=24 mm. 99
Table 28. -60+70 Low density glass beads; K=2, bed depth=24 mm. 100
Table 29. -60+70 Low density glass beads; K=0, bed depth=24 mm. 101
Table 30. -60+70 Low density glass beads; K=4, depth=1 mm. 103
Table 31. -60+70 Low density glass beads; K=2, bed depth=1 mm. 104
Table 32. -60+70 Low density glass beads; K=0, bed depth=1 mm. 105
Table 33. -100+140 Master Beads; K=4, bed depth=1 mm. 107
Table 34. -100+140 Master Beads; K=2, bed depth=1 mm. 108
Table 35. -100+140 Master Beads; K=0, bed depth=1 mm. 109
Table 36. -100+140 Low density glass beads; K=4, depth=1 mm. 111
Table 37. -100+140 Low density glass beads; K=2, bed depth=1 mm. 112
Table 38. -100+140 Low density glass beads; K=0, bed depth=1 mm. 113
Table 39. Synthesis of mass transfer results 115
Table 40. Minimum fluidization velocity. 117

1.0 Introduction

This thesis presents results of experimental determination of mass transfer from particles in an aerated vibrated bed to gas passing upward through the bed. The work uses a classical approach, in which the amount of naphthalene subliming from particles coated with this substance provides a measure of mass transfer. The particles employed are closely sized fractions of either glass beads or "Master Beads" — the latter being nearly spherical particles of a dense, crude alumina.

This introductory chapter places the aerated vibrated bed in context with the fluid bed and the non aerated vibrated bed. The chapter comments briefly upon the literature on vibrated beds and aerated vibrated beds, and discusses in more detail the literature on experimental determination of mass transfer. There follows an introduction to the mechanics of vibrated beds and a statement of the scope of the experimental program reported in the present study.

1.1 Review of Fluidization

Kunii and Levenspiel, in *Fluidization Engineering* (1969), define fluidization as the "operation by which fine solids are transformed into a fluidlike state through contact with a gas or liquid." These authors discern several kinds of fine particle beds depending upon the flow rate. Figure 1 on page 4 shows the several different behaviors that can be distinguished when a gas is passed upward through the bed of particles. When, at very low flow rate, the fluid passes only through the void spaces between stationary particles, the bed is called a ***Fixed Bed***. For this bed, the pressure drop, correlated by Ergun (1952), which represents the viscous and the kinetic energy losses of the fluid flowing through the bed, increases with the rise in superficial gas velocity; at low Reynolds Number, the increase is linear. When the pressure drop across the bed becomes equal to the weight of the fluid and particles, the bed is at its ***Minimum Fluidization Velocity***, U_{mf}, and it takes on properties of a fluid. With further increase in gas flow rate, the bed may or may not expand isotropically. Fine particles (a Geldart Group A solid) undergo expansion, often appreciable, between U_{mf} and a ***Minimum Bubbling Velocity*** (U_{mb}), at which bubbles appear, rising through the solid mass. For such particles, U_{mf} might well be termed the ***Minimum Buoyancy Velocity***. For larger particles (a Geldart Group B solid), negligible isotropic expansion occurs after minimum fluidization — i.e., ***Minimum Buoyancy*** and ***Minimum Bubbling Velocities*** are indistinguishable. In the ***Bubbling Fluid Bed***, gas bubbles induce a strong particle circulation. Pressure drop becomes almost constant. The gas-fluidized bed is considered to be a ***Dense-Phase Fluid Bed*** as long as a top surface is clearly defined (Kunii and Levenspiel, 1969). However, at very high flow rate, the top surface disappears and the solid particles are entrained by the fluid stream from the bed. This state is known as a ***Lean-Phase Fluid Bed***, with pneumatic transport of solids.

A dense-phase, gas-fluidized bed has a liquidlike behavior, looking much like a boiling liquid. A light object will float at the top surface of the bed. If the vessel is tilted, the top surface will remain horizontal. Solids will flow through a hole in the side of the container. If two vessels are connected, their levels will equalize.

Determination of U_{mf} is relatively easy for Geldart Group B particles, simply from an observation of the velocity at which bubbles begin to appear in a bed. For Group A particles, determination of U_{mf} is best provided by a plot of pressure drop versus velocity (e.g., a plot like Figure 2 on page 5, for a bed of uniformly sized sand particles). The two regions, fixed bed and fluid bed, are characterized respectively by a rising and a constant pressure drop. Beyond U_{mf} , the pressure drop often rises to a maximum value, distinctly beyond that observed subsequently when the minimum bubbling velocity has been achieved. Soil mechanical forces tend to hold the bed in place and "delay" the appearance of bubbles. At U_{mb}, these forces are overcome and all but disappear. Beyond U_{mb}, the pressure drop is constant.

According to Geldart (1973) and Grace's (1986) classifications of solid powders, most of the particles experimented with in the present work belong to Group B ($100 \leq \bar{d}_p \leq 800$ μm). The -16+30 mesh particles are just situated at the B-D groups boundary (Group D: $\bar{d}_p \leq 1$ mm). (For a complete description of the particles used, refer to Section 2.2 on page 25.)

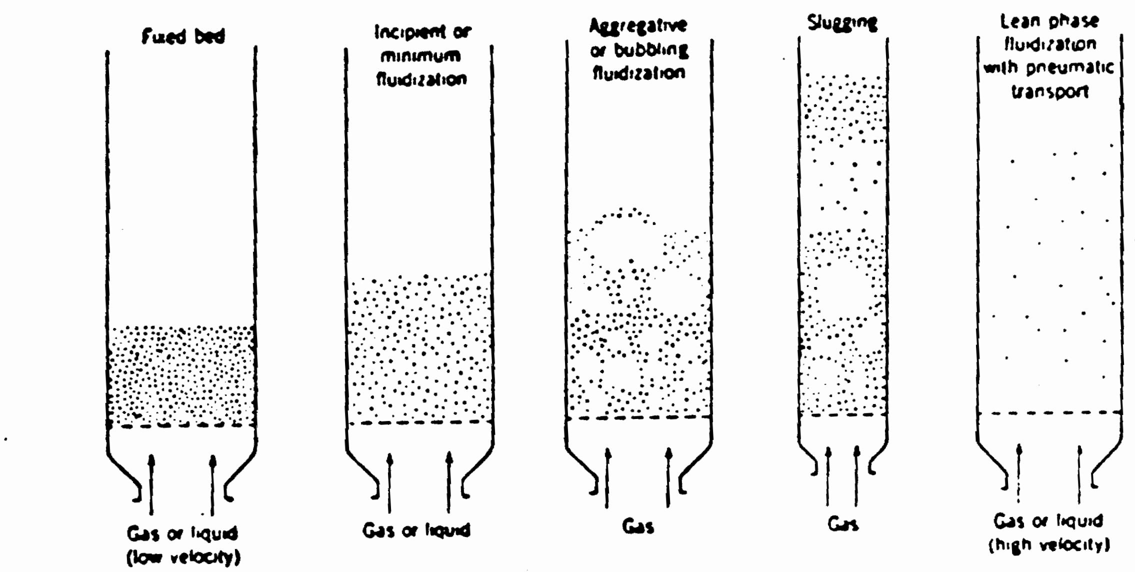


Figure 1. Various kinds of contacting of a batch of solids by gas: from Kunii and Levenspiel, 1969.

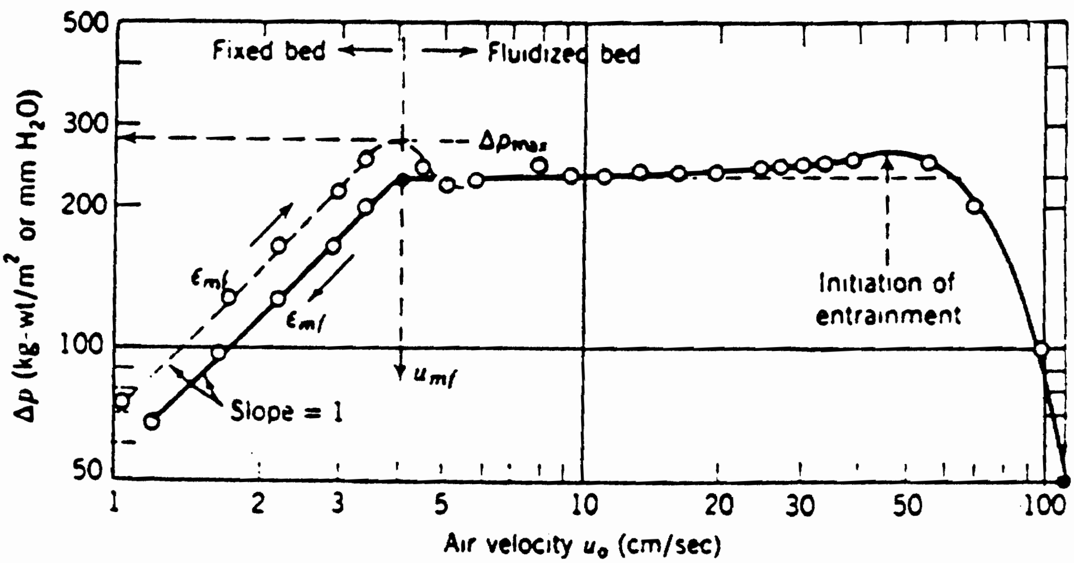


Figure 2. Pressure drop versus gas velocity for a sand particles bed: from Shirai, 1958.

1.2 Background on Vibrated Beds

Another way to "fluidize" a bed of fine particles is to subject the bed to mechanical vibrations of appropriate intensity and frequency.

In our terminology, a ***Vibrated Bed*** is a mobile layer of solid particles contained in a vessel that is vertically vibrated. Within a frequency range of 5 to 100 Hz the particles become mobile, the bed porosity increases and a fluidlike state is reached (Gutman, 1974). Beyond 100 Hz, the circulation of particles is very slight; below 5 Hz, vibrational amplitudes required to create bed mobility are unduly large. The first investigations on vibrated beds were conducted by Bachmann (1940), who described the dynamic behavior of granular solid particles mechanically vibrated in a cylindrical vessel. However, it was only after the work of Chlenov and Mikhailov (1965) that practical applications of vibrated beds appeared. They demonstrated that the bed became more porous and more mobile as the intensity of vibration was increased.

Some authorities use the terms "vibrofluidization" and "vibrofluidized bed". We avoid these terms, since the vibrated bed is strikingly different from the more familiar gas-fluidized bed. The former does not exhibit a fluidlike behavior comparable to those seen in the fluid bed (Thomas *et al.* 1987). For instance, the top surface of a vibrated bed, in general, is not level. It is possible, for very fine particle sizes (below 100 μm), to maintain different levels in the two arms of a U-tube that is vibrated — something not seen if the two arms are gas-fluidized. The material even flows so as to increase the disparity in levels (Gutman, 1974). For these reasons, the term vibrated bed may be more appropriate than vibrofluidized bed, even if the latter is commonly used in the literature.

Before any further discussion, more definitions must be given. If a flow of gas, less than the minimum fluidization velocity for the bed (U_{mf}), is maintained through the vibrated bed, we refer to the bed as an ***Aerated Vibrated Bed.*** If the gas flow is greater than U_{mf} for the bed, the particles become fluidized by the gas in the ordinary sense of the word "fluidized." In this case, we call the bed a ***Vibrated Gas-Fluidized Bed.***

The application of vibrated beds or aerated vibrated beds in the treatment of particles has been reported in many engineering fields. They mainly find use for conductive and convective drying of materials such as sugar, tea, pharmaceuticals such as antibiotics, and polymers (Danielsen and Hovmand, 1980). According to Pakowski *et al.* (1984), drying processes represent 90% of vibrated-bed applications. Mechanical vibrations are also used for coating polymer layers onto hot metal objects or to mobilize a mass of powder to be used as a cooling medium in the heat treatment of steels (Gutman, 1974).

1.3 Mass Transfer in Fluidized Beds

Kunii and Levenspiel, in *Fluidization Engineering* (1969), have used published investigations to support their analysis of mass transfer in light of their model for the bubbling fluid bed. For the purpose of our study, only publications on naphthalene-air systems and work on shallow beds have been kept.

Little investigation appears to have been performed using aerated vibrated beds. Nevertheless, Sunderland and Ahmed, in *Mass Transfer in a Vibrated Reactor* (1981), measured the mass transfer coefficient in a reactor where mixing was obtained by means of a magnetically driven piston reciprocating at high speed.

Table 1 on page 10 gives a summary of the previous investigations considered here. Experimental results concerning fluidized beds are reported in Figure 3 on page 11. Figure 4 on page 12 represents the results obtained by Sunderland and Ahmed.

For both figures, the Sherwood Number is defined as:

$$Sh = \frac{k_d \bar{d}_p}{D} \qquad [1.1]$$

where k_d is the mass transfer coefficient (m/s), $\bar{d}_p$ the particle diameter (m), and D the diffusion coefficient (m^2/s).

The Reynolds Number is:

$$Re = \frac{u_0 \bar{d}_p}{\nu} \qquad [1.2]$$

where ν is the kinematic viscosity (m^2/s) and u_0 the superficial velocity of the gas. Sunderland and Ahmed have taken into accont the velocity due to the motion of the piston in addition to the gas velocity. The two effects have been supposed to be independent of each others so that it has been possible to calculate a root mean square velocity for the piston and, by summing the two velocities, to determine a modified Reynolds number.

Assuming that the motion of the piston is a simple harmonic, its velocity is:

$$v_p = a_0 \omega \cos \omega t \qquad [1.3]$$

where a_0 is the amplitude, ω the angular frequency, and t the time.

The root mean square velocity is:

$$v_{p,rms} = \sqrt{\frac{a_0\omega}{2\pi}\int_0^{2\pi} (\cos\theta)^2 d\theta} = \sqrt{\frac{a_0\omega}{2}} \qquad [1.4]$$

where $\theta = \omega t$, therefore the modified Reynolds number is:

$$Re = \frac{\bar{d}_p(u_0 + \sqrt{\frac{a_0\omega}{2}})}{\nu} \qquad [1.5]$$

Influence of Particle Size and Density

Although gas-fluidized-bed data in Figure 3 on page 11 represent many varying experimental conditions and different particle types, a trend of increasing Sherwood Number with increasing particle size can be observed — i.e. increasing mass transfer coefficient.

In work with beds with mechanical mixing, Sunderland and Ahmed have noticed two different patterns, shown in Figure 4 on page 12. For frequencies below 15 Hz, where the contribution of vibration was significant, the trend remains the same as previously described. Surprisingly, for higher frequencies, the trend is inverted: that is to say, Sherwood Number decreases with increasing particle size. The two transfer regimes are characterized by:

$$Sh \propto Re^{0.5} \qquad [1.6]$$

for low frequencies, and by:

$$Sh \propto Re^{1.3} \qquad [1.7]$$

for higher frequencies. The authors pointed out that the relative location of the two regimes depends to some extent on the flow rate, amplitude, and particle size. According to Sunderland and Ahmed, this change in the dependence of mass transfer upon Reynolds Number may arise from the destruction of some boundary layer, from wake shedding, or from some change associated with the relaxation of turbulence.

Table 1. Experimental conditions used in previous mass transfer studies

Authors	Gas	System	Particle Type and Size (μm)	Bed Diameter (mm)	Bed Height at Rest (mm)
Resnick and White (1949)	air, H_2 CO_2	sublimation of naphthalene	pure naphthalene (spherical) 210-1700	22, 31 and 44	12.7-25.4
Chu *et al.* (1953)	air	sublimation of nalhthalene	coated glass beads (spherical) 726, 737 and 693	102	2.54-50.8
Ridchardson and Szekely (1961)	air	adsorption of iso-octane or toluene	silica gel, activated carbon, charcoals (spherical) 88-2576	30	$5d_p$
Sunderland and Ahmed (1981)	air	evaporation of naphthalene in a vibration mixed reactor	pure naphthalene pellets (spherical) 3200, 4800, and 6400	----	----

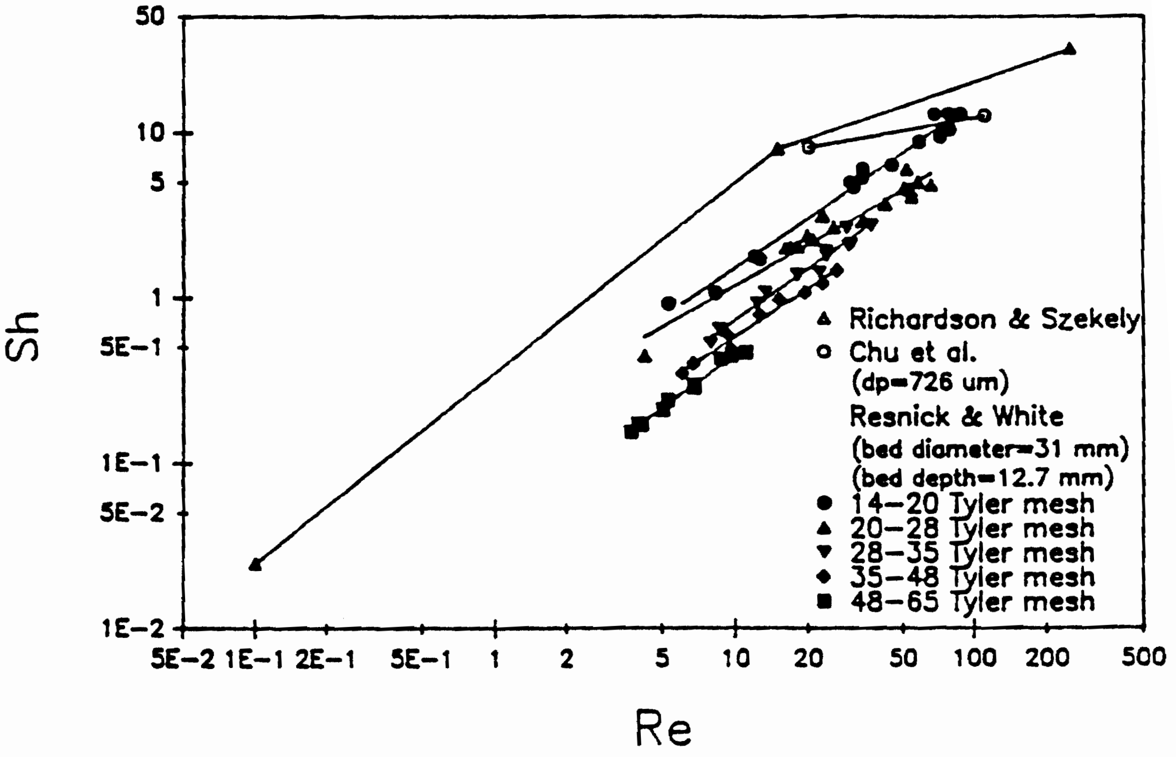


Figure 3. Experimental mass transfer in gas fluidized systems.

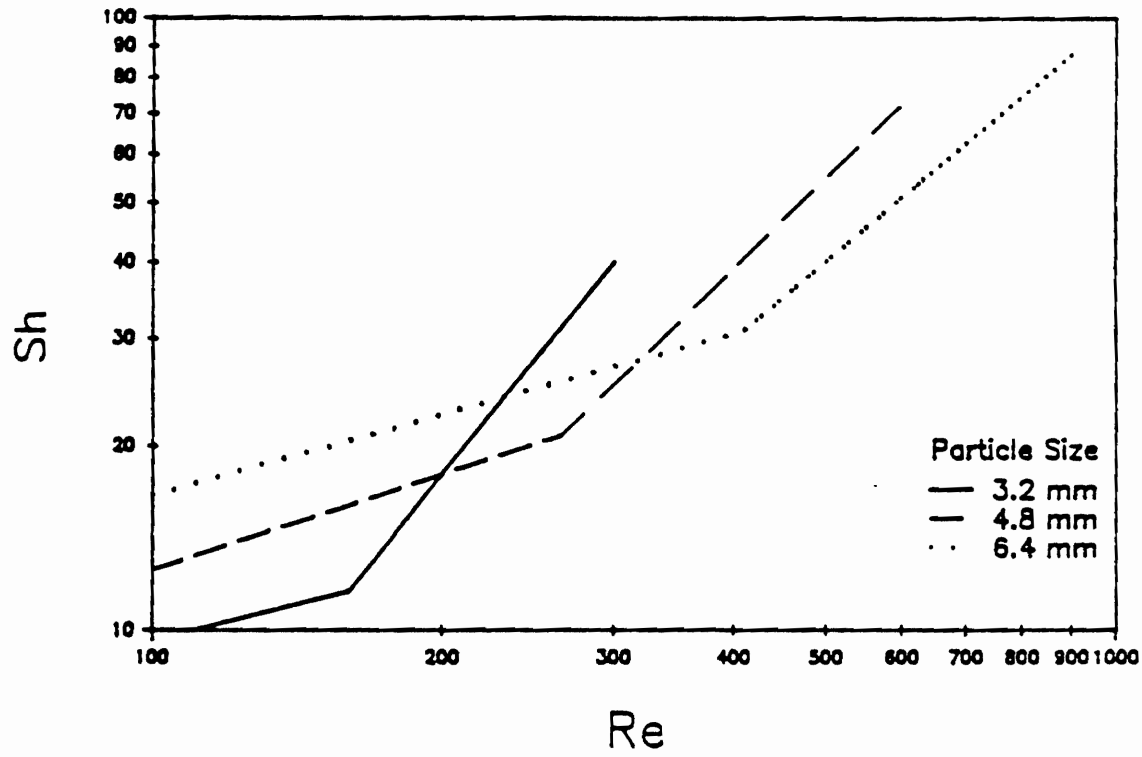


Figure 4. **Experimental results with mechanical mixing:** 3.2 mm amplitude and 8 $\mu m^3/s$ flowrate, from Sunderland and Ahmed, 1981.

Chu *et al.* (1953) have used a wide range of particles of different densities. According to these authors, the mass transfer coefficient in a fluid bed is independent of particle density. This variable, however, is an important factor in determining the minimum fluidization velocity.

Effect of Bed Diameter

Figure 5 on page 14 is a synthesis of the Resnick and White (1949) investigation on the effect of bed diameter on fluidized-bed mass transfer. The points obtained for 31 and 44-mm tubes were satisfactorily correlated, since the two lines drawn were within the limits of their experimental error. Values for the 22-mm tube were consistenly lower than those for the other two tubes. A wall effect was thus in evidence for the experiments using the smallest tube, which disappeared when the 31-mm tube was used. (Refer to Appendix A for a conversion Tyler mesh screen to particle diameter.)

Effect of Initial Bed Height

All investigators agree that bed height as measured at rest seems not to affect mass transfer rates in deep fluid beds. Figure 6, on page 16, gives illustrative data, from Resnick and White. Their runs used 48-65 and 20-28 Tyler mesh naphthalene particles, fluidized by air at 12.7-mm and 25.4-mm bed heights. Since all the data, for each particle size, can be correlated by one line, no effect of bed height is seen.

Nevertheless, in ultra-shallow beds, higher mass transfer rates have been observed. Richardson and Szekely measured mass transfer rates in shallow beds, about five particle diameters in height, by unsteady adsorption of iso-octane or toluene vapor from the

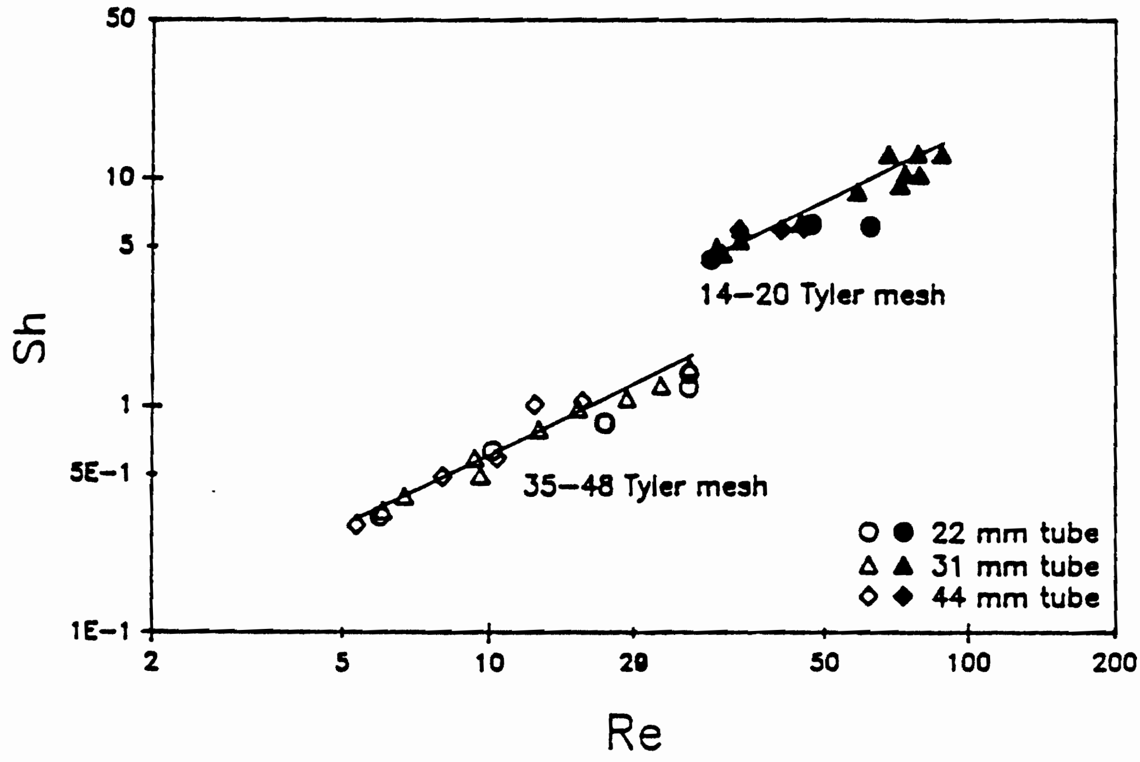


Figure 5. Effect of bed diameter on mass rates in fluidized beds: from Resnick and White, 1949.

fluidizing air. Considering the overall mass transfer coefficient, the authors obtained these correlations:

$$Sh = 0.374 Re^{1.18} \quad [1.8]$$

for $0.1 < Re < 15$

$$Sh = 2.01 Re^{0.5} \quad [1.9]$$

for $15 < Re < 250$

These lines are shown in Figure 3 on page 11.

1.4 Mechanics of Vibrated Beds

A mathematical description of particle behavior in an aerated vibrated bed are not be provided in this thesis. Nevertheless, the reader should understand the motion of the vessel and bed when they are subjected to vertical vibrations only.

The displacement of the vessel vibrated at a frequency f is given at any instant t by:

$$a = a_0 \sin \omega t \quad [1.10]$$

where ω is the angular frequency and a_0 is the amplitude. The vessel velocity is:

$$\dot{a} = a_0 \omega \cos \omega t \quad [1.11]$$

and the acceleration:

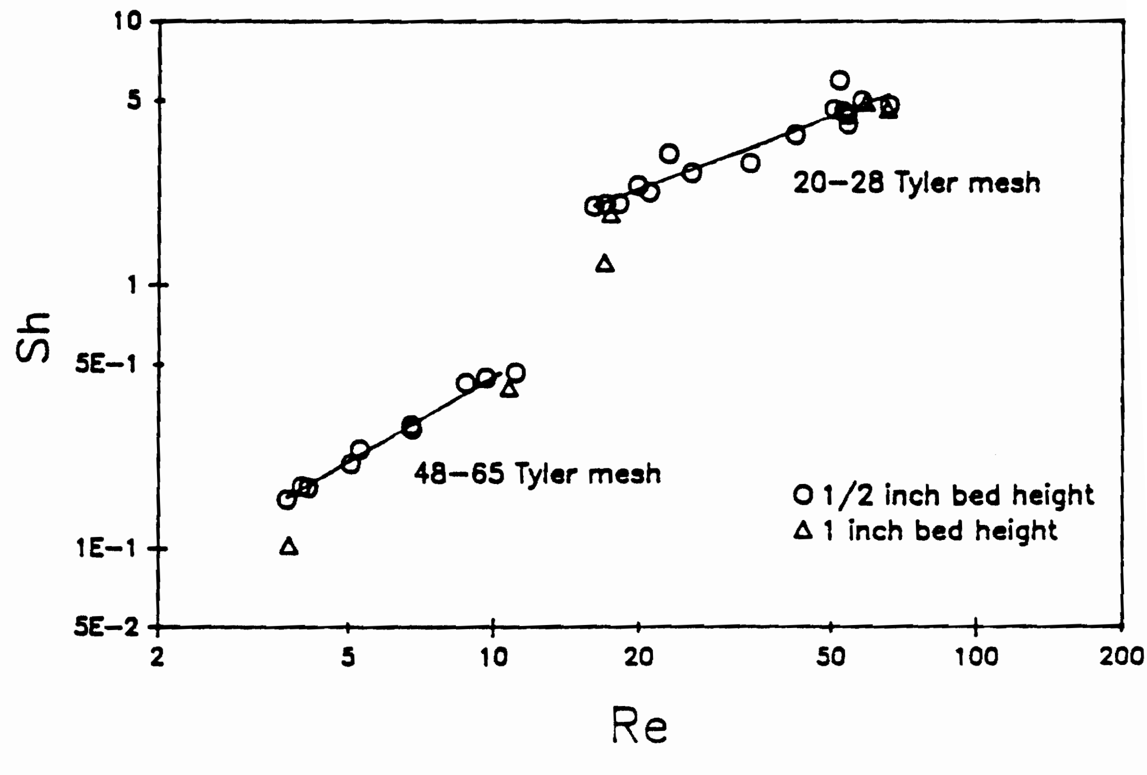


Figure 6. Effect of bed height on mass rates in fluidized beds: from Resnick and White, 1949.

$$\ddot{a} = - a_0\omega^2 \sin \omega t \qquad [1.12]$$

A dimensionless vibrational intensity parameter, K, is defined as the ratio of the maximum vibrational acceleration to gravitational acceleration g:

$$K = \frac{\max \mid -a_0\omega^2 \sin \omega \mid}{g} = \frac{a_0\omega^2}{g} \qquad [1.13]$$

Consider a particle at the bottom surface of a vessel. As the vessel moves upward it decelerates. At first, the particle remains in contact with the floor. As soon as the acceleration becomes less than -1 g, however, the particle will separate from the floor. As the particle is in flight, the vessel continues its sinusoidal motion downward; subsequently, the vessel reverses direction, and moves upward. In its upward motion, the vessel collides with the particle. If the collision is perfectly plastic — i.e., the particle does not rebound after collision — it will remain in contact with the vessel until its acceleration again falls below -1 g. In a vibrated bed at a depth greater than a few particle diameters, the mass of particles behaves as a perfectly plastic body; they move as a coherent mass (Bachman 1940; Thomas *et al.* 1989). This behavior is illustrated in Figure 7 on page 18. Notice that, for K less than or equal to one, a bed of particles never lifts off the vessel floor.

Our mass-transfer experiments have been made for several values of K up to K = 4, the highest vibrational intensity allowed by the vibration equipment.

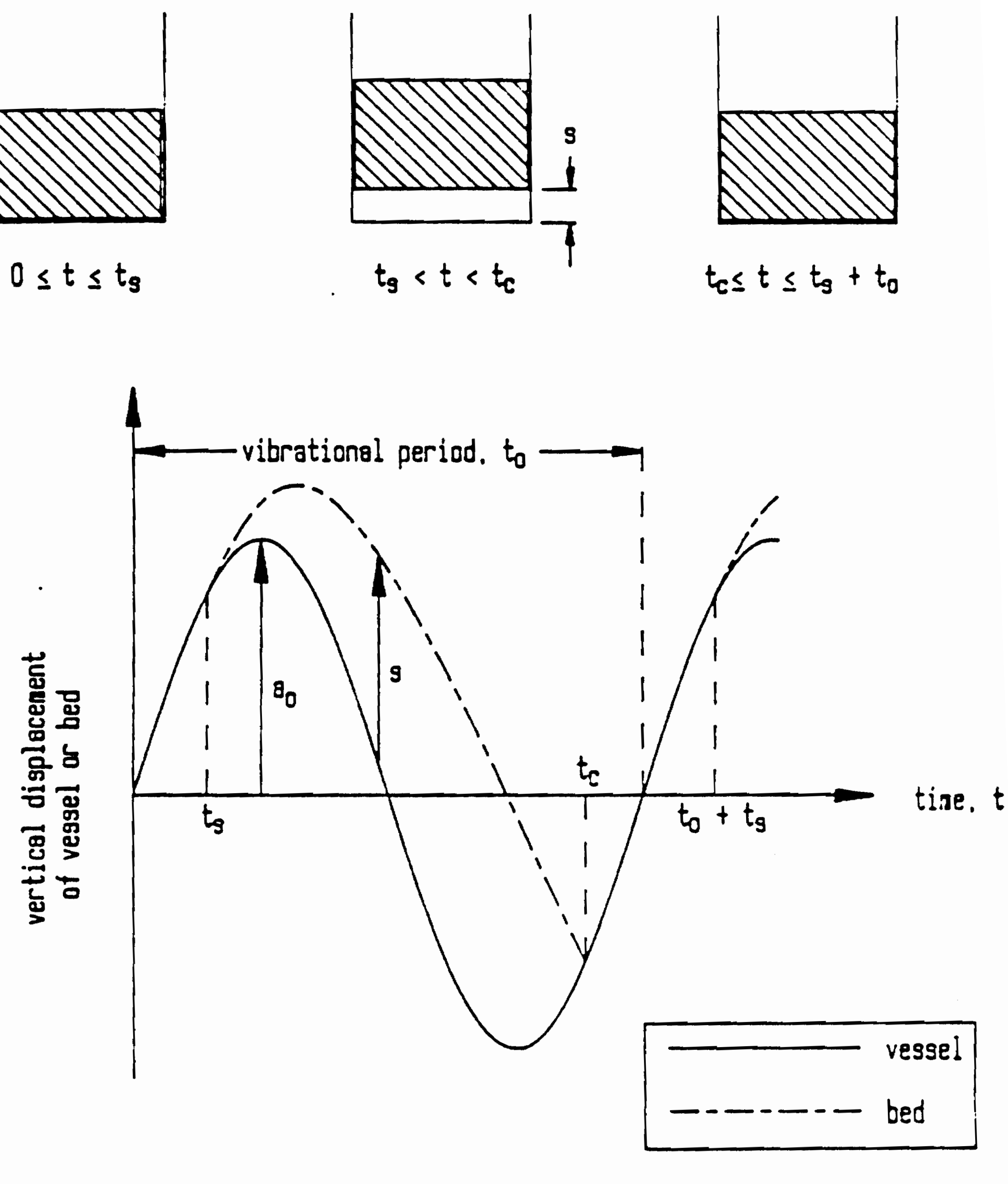


Figure 7. The bouncing motion of a vibrated bed: the bed is modeled as a porous plastic body. (from Thomas, 1988). It lifts off from the vessel base at time t_s, collides at time t_c; t_0 represents the vibrational period.

1.5 *Scope of This Study*

The primary objective of this study is to determine how vibrations, in an aerated vibrated bed, affect the mass transfer coefficient. The study's results may be important for predicting how reaction rates, using gaseous reactants and solid catalyst, are controlled in chemical reactors subjected to vibrations.

We have conducted experiments using shallow and ultra-shallow aerated vibrated beds. A bed is called shallow when the value of the ratio of the height-to-diameter (L/D) of the bed is about 0.5. If $(L/D) << 1$, the bed is described as ultra-shallow.

Beds of different particle sizes and densities were used, vibrated at different K values up to 4, and aerated by nitrogen.

The aims of the present thesis are:

- to provide results describing mass transfer between a particle bed and a flowing fluid;
- to observe effects of particle size, density, vibration intensity, and bed height on mass transfer coefficient.

2.0 Experimental Work

We have determined mass transfer coefficients for cylindrical beds of naphthalene-coated beads, vibrated at a frequency of 25 Hz, and aerated by nitrogen. Mass transfer is inferred from naphthalene content of nitrogen leaving a bed, as determined by gas chromatography.

This section describes our equipment and the particles used in this study, shows how the data are used to derive overall mass transfer coeficients; and discusses the gas chromatograph calibration.

2.1 Apparatus

Figure 8 on page 22 provides a schematic diagram of the equipment. Pre-purified nitrogen, our fluidizing gas, is supplied from a tank situated upstream of the installation. The gas is passed through a 3-way valve allowing two paths: one directly into the 1/8-in. sampling line, in order to clean this line and a sampling loop of any deposits of naphthalene remaining from a previous run; and a second path to the vibrated bed. The second stream is devided into two 1/4-in. lines, in which flow rates are controlled by two metering valves. The nitrogen flow is measured, in each line, by a mass flowmeter of 0 to 20 l/min range. Each of the two mass flowmeters has been calibrated before the experiments against a wet test gas meter; the reading error of a flowmeter is approximately ± 0.1 l/min. Downstream from each mass flowmeter, a check valve is mounted in the line, to avoid a return flow of gas.

Nitrogen is supplied to the bed via a 1/4-in.-diameter orifice situated at the bottom of the vessel. In order to obtain an even distribution of gas through the bed, a grid plate of relatively high pressure drop (40 μm of equivalent pore size) is used as a porous medium. The vessel, as shown in Figure 9, on page 24, is a plexiglas cylinder, 312 mm in height, 50 mm internal diameter, and having 1/4-in. walls. Another 1/4-in. orifice is situated on the vessel and under the grid plate, permitting a determination of total pressure drop (bed plus grid plate) when the bed is not vibrated. Pressure is determined by M.K.S. INSTRUMENTS pressure transducers (model PDR-D.1) with 0 to 10 mmHg range.

The vibration equipment includes a DYNASCAN function generator, which electronically generates a sinusoidal wave. A DYNASCAN frequency counter (model 1803), coupled with the function generator, allows an accurate setting of frequency, which was 25 Hz during all of the experiments. The signal, amplified by a transductance amplifier manufactured by V.G. DIGITAL ENG., drives a LINGDYNAMIC SYSTEM electromagnetic vibrator (model 203), which provides the mechanical vibrations.

In an electromagnetic vibrator, a coil is positioned axially within a hollow, cylindrical permanent magnet. The coil is suspended by a set of thin leaf-springs. When an alternating current passes through the coil, it moves upward and downward at an amplitude that depends on the polarity and the magnitude of the applied voltage.

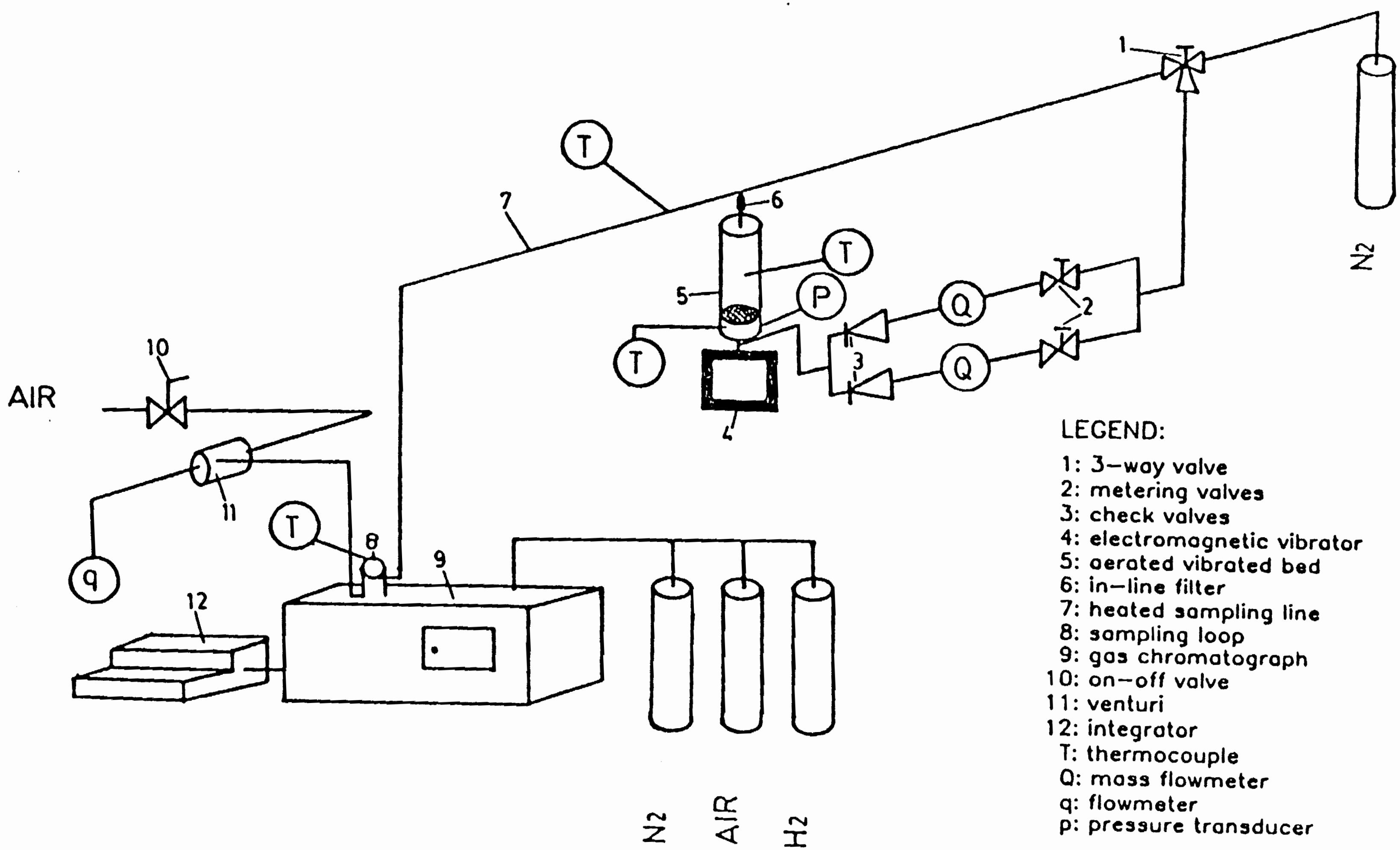


Figure 8. Schematic drawing of the equipment.

Four 1/4-in. rods attach the vibrated vessel to a rectangular steel plate, which is suspended by four leaf-springs from a fixed steel frame. The stiffness of the leaf springs are adjusted, by using different numbers of leaves, according to the weight of the bed to give resonance at the frequency used in the study. The steel plate is mechanically linked to the vibrator by a no 10-24 screw, which transmits the vibratory motion to the bed vessel. Vessel acceleration is measured by an accelerometer fixed onto the vibrating steel plate. Output is given by a VIBRAMETRICS. INC. accelerometer (Model M8D), which directly gives the vibration intensity parameter K.

Bed temperature is measured by two J-thermocouples (Iron-Constantan) of 0 to 400°C temperature range. In order to observe any temperature gradient within the bed, one thermocouple is placed horizontally close to the grid plate, while a second is placed close to the vertical wall of the cylinder. A third J-thermocouple is placed above the particle bed, in the middle of the vessel, and measures the temperature of the gas leaving the bed. Two other identical thermocouples are used: one on the heated sampling line, and the second recording the temperature of the sampling loop of the gas chromatograph. Five channels of a thermocouple amplifier OMEGA DIGITATOR TM is used to indicate the five temperatures. The amplifier contains a linearizing circuit for J-thermocouples, so that the intrinsic error is 0.1°C; the total error is estimated to be approximately ±0.5°C.

An air venturi sucks a sample of the gas leaving the bed through a 7-μm filter, which prevents naphthalene solids from being sucked, via a 1/4-in. sampling line into a sampling loop. The sampling line is heated at a higher temperature than the bed by electrical resistance heating from two variable powerstats. Heating of the line avoids the condensation of sublimed naphthalene.

A HEWLETT PACKARD gas chromatograph (model 4730 A) determines the naphthalene content of the bed offgas. The volume of gas for analysis is fixed by a 5

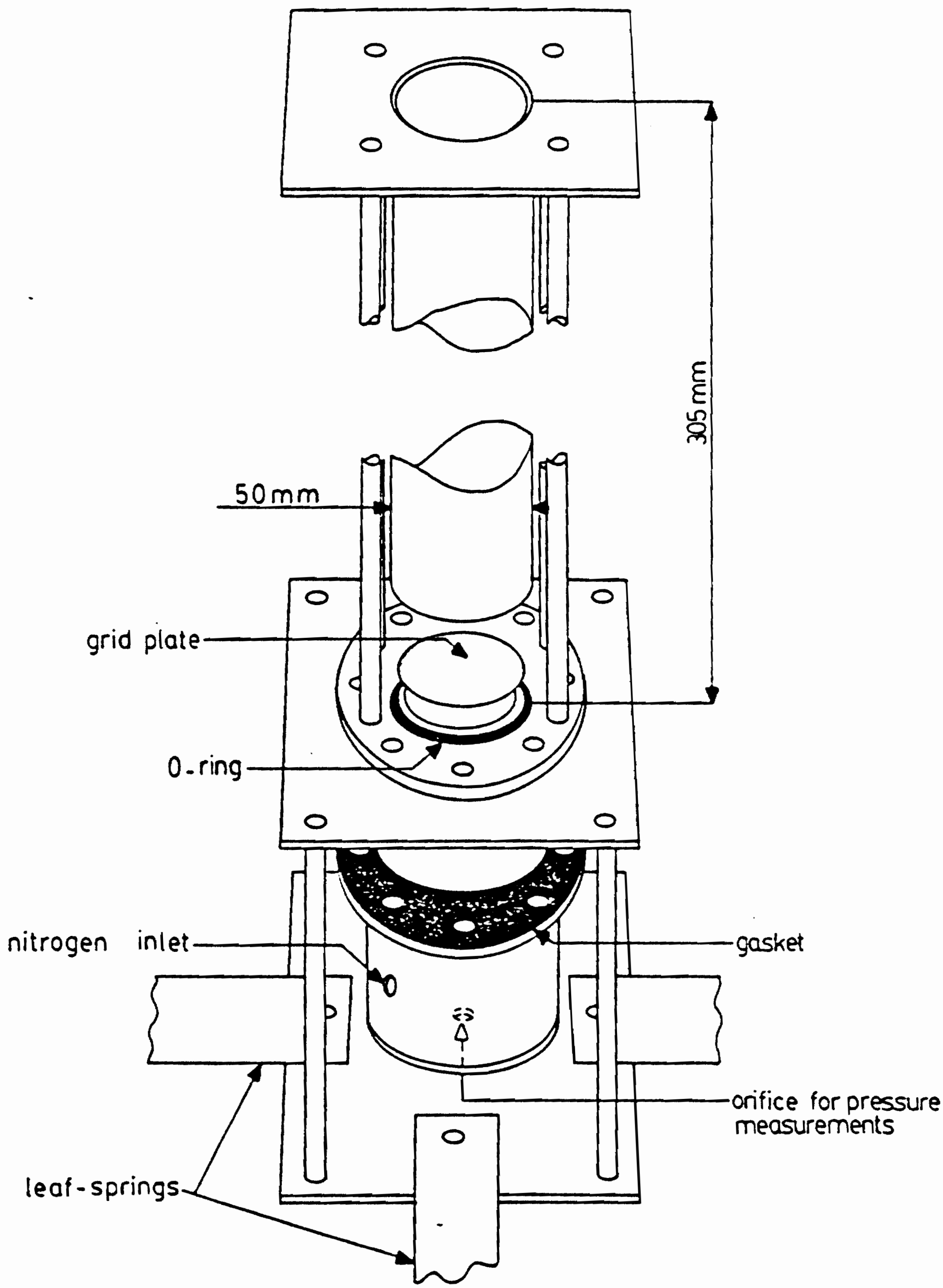


Figure 9. Aerated Vibrated Bed: the drawing shows the cylindrical vessel as well as the fixing system.

cc sampling loop, and injection is driven by two HUMPHREY solenoid valves. Nitrogen of 4.5 grade is used as carrier gas; CGA grade air, and 4.5 grade hydrogen are used for the flame ionization detector of the gas chromatograph. The gas chromatographic response is recorded as a peak on a HEWLETT PACKARD integrator, model 3390 A.

2.2 *Particle Types, Sizes, and Densities*

For use in the experiments, two types of coarse particles have been coated with naphthalene:

Master Beads: Almost spherical, these black particles contain about 86% alumina, 2-4% silica, 6-8% iron oxide, and 4-5% titania in a solid solution. Their density is roughly 3,650 kg/m^3. Master Beads are manufactured by Norton-Alcoa.

Low Density Glass Beads: Almost perfectly spherical, these "P-series glass beads" are made of ordinary soda-lime silicate glass. Their density is 2,500 kg/m^3. They are manufactured by Potter's Industries.

Naphthalene coating of the two kinds of particles was performed by Coating Place, Inc., using naphthalene flakes of a density of 1145 kg/m^3 from Aldrich Chemical Company, Inc..

After the beads were coated, they are separated by size. Table 2, on page 27, gives the size ranges in U.S. Standard mesh numbers and in equivalent size in microns for the coated beads used in our experiments. We have calculated the geometric mean $\bar{d}_p$ of each set of beads:

$$\bar{d}_p = \sqrt{d_{p,u} d_{p,l}} \qquad [2.1]$$

where $d_{p,u}$ is the upper limit of the size range in microns and $d_{p,l}$ the lower one.

We estimated densities of the coated beads with the assumption that the coating of naphthalene is uniform. With this assumption, the increase of weight of a particle is:

$$m_{total} = m_{bead} + m_{naphthalene} \qquad [2.2]$$

where:

$$m_{bead} = \frac{\pi \bar{d}_b^{\,3}}{6} \rho_b \qquad [2.3]$$

$$m_{naphthalene} = \frac{\pi(\bar{d}_t^{\,3} - \bar{d}_b^{\,3})}{6} \rho_n \qquad [2.4]$$

$$m_{total} = \frac{\pi \bar{d}_t^{\,3}}{6} \rho_t \qquad [2.5]$$

$\bar{d}_b$ and $\bar{d}_t$ represent the geometric mean size of the initial bead and coated bead, respectively. The quantity ρ_b is the density of the initial bead and ρ_n of the naphthalene. Substituting equations [2.3], [2.4], and [2.5] in [2.2], we can express the total density of the coated particle as:

$$\rho_t = \frac{[\rho_b \bar{d}_b^{\,3} + (\bar{d}_t^{\,3} - \bar{d}_b^{\,3})\rho_n]}{\bar{d}_t^{\,3}} \qquad [2.6]$$

Table 2. Size ranges and densities of coated beads.

Master Beads

U.S. Standard Mesh Size	Size Range (μm)	Geometric Mean Size (μm)	Density (kg/m^3)
-16 +30	595-1190	841	2633
-40 +50	297-420	353	1829
-60 +70	210-250	229	2302
-100 +140	105-149	125	2019

Low Density Glass Beads

U.S. Standard Mesh Size	Size Range (μm)	Geometric Mean Size (μm)	Density (kg/m^3)
-16 +30	595-1190	841	1950
-60 +70	210-250	229	1770
-100 +140	105-149	125	1618

2.3 *Mass Transfer Theory*

Based on the total surface of contact A (m^2) of the particles in the vessel, the overall mass transfer coefficient k_d (m/s) for sublimation of solid naphthalene by the fluidizing nitrogen can be expressed as:

$$\frac{-1}{A}\frac{dN_n}{dt} = k_d(C_{nb} - C_{ns}) \tag{2.7}$$

N_n : moles of naphthalene

C_{nb} : concentration of naphthalene within the bulk flow, (mole/m^3)

C_{ns} : concentration of naphthalene in the film surrounding the surface of the particle, (mole/m^3).

Considering the mixture of sublimed naphthalene in nitrogen to be an ideal gas, we can express the concentration of naphthalene as a function of its partial pressure as:

$$C_n = \frac{p_n}{RT} \tag{2.8}$$

where p_n is the partial pressure of naphthalene in the gas phase, (Pa); R is the universal gas constant, (J/mole/K); and T is the absolute temperature of the gas, (K).

Moreover, the molar flow can also be written, using equation [2.8], as:

$$\frac{dN_n}{dt} = \frac{p_n}{RT}\dot{Q} \tag{2.9}$$

where $\dot{Q}$ is the volumetric flow rate of the gas stream, (m^3/s). Therefore, substituting equations [2.8] and [2.9] in [2.7], we obtain:

$$-\frac{p_n}{RT}\frac{\dot{Q}}{A} = \frac{k_d}{RT}(p_n - p_{n,sat}) \qquad [2.10]$$

The final expression of k_d is then:

$$k_d = \frac{-\dot{Q}/A}{(1 - \frac{p_{n,sat}}{p_n})} \qquad [2.11]$$

The total surface of contact of naphthalene with the gas stream is:

A = (total volume of the particles contained in the bed) (specific surface of a particle)

$$A = (\frac{M}{\rho_t})(\frac{6}{\bar{d}_t}) \qquad [2.12]$$

where M is the total mass of the bed (kg).

Mass transfer coefficient is commonly expressed in dimensionless form, by use of the Sherwood Number:

$$Sh = \frac{k_d \bar{d}_t}{D} \qquad [2.13]$$

We have estimated the diffusion coefficient D of the naphthalene-nitrogen system with use of the modified Maxwell formula given by Gilliland (1934):

$$D = \frac{0.0043 T^{3/2}\sqrt{1/M_a + 1/M_b}}{(V_a^{1/3} + V_b^{1/3})^2 P} \qquad [2.14]$$

where:

D: diffusion coefficient, (cm^2/s)

T: absolute temperature of the gases, (K)

P: total pressure, (atm.)

M_a, M_b : molecular weights of the two gases (naphthalene, nitrogen)

V_a, V_b : molar volumes of the two gases at their normal boiling points.

The parameters for nitrogen (N_2) and naphthalene ($C_{10}H_8$) are:

$$M_{N_2} = 28.016\ g/mol$$

$$M_{C_{10}H_8} = 128.164\ g/mol$$

$$V_{N_2} = 34.85\ cm^3/mol$$

$$V_{C_{10}H_8} = 147.6\ cm^3/mol$$

while T and P are considered as variables in determining the Sherwood Number.

2.4 *Calibration of the Gas Chromatograph*

2.4.1 Experimental System

The gas chromatograph calibration was conducted by replacing the aerated vibrated bed shown in Figure 8, on page 22, by an isothermal saturator filled with naphthalene and in which a flow of nitrogen is maintained. The saturator consists of a 130 cm long, 1/4-in.-diameter stainless steel tube packed with naphthalene flake. The tube is situated inside a larger, 7-cm diameter P.V.C. tube. The two tubes are of the same length, and the outer tube is well insulated. Together, the two tubes provide for heat exchange between a flow of water in the P.V.C. tube and a countercurrent flow of nitrogen to be saturated with naphthalene. Figure 10, on page 32, depicts the arrangement. The flow of water is provided from a FISHER SCIENTIFIC refrigerated bath (model 90).

The outlet of the saturator tube is connected to the sampling line via a 1/4-in. brass tube, filled with glass wool to act as a filter against naphthalene fines that may enter the sampling line.

Two 150-cc presaturators, also filled with naphthalene flakes, are mounted in line upstream from the saturator and placed in the aforementioned refrigerated bath. The top of each presaturator is filled with glass beads so as to obtain a uniform distribution of the nitrogen flow through the naphthalene flakes. A 1/4-in. brass serpentine precooler, 1.5 m long and filled with glass beads, is placed in the refrigerated bath between the nitrogen tank and the first presaturator, in order to cool the gas.

Temperature control of the refrigerated bath is ensured by an OMEGA miniature P.I.D., Proportional-Integral-Derivative, microprocessor controller series CN 9000, with P.D.P.I., Proportional-Derivative-Proportional-Integral, approach for optimal control during startup and steady-state operation. The resolution of this temperature controller is 0.1°C.

Four J-thermocouples of 0 to 400°C range give temperatures of the refrigerated bath and saturator inlet and outlet. One thermocouple is placed just inside the heat exchanger outlet, and a second just outside. The J-thermocouple amplifier decribed on page 23 is used to read the several temperatures.

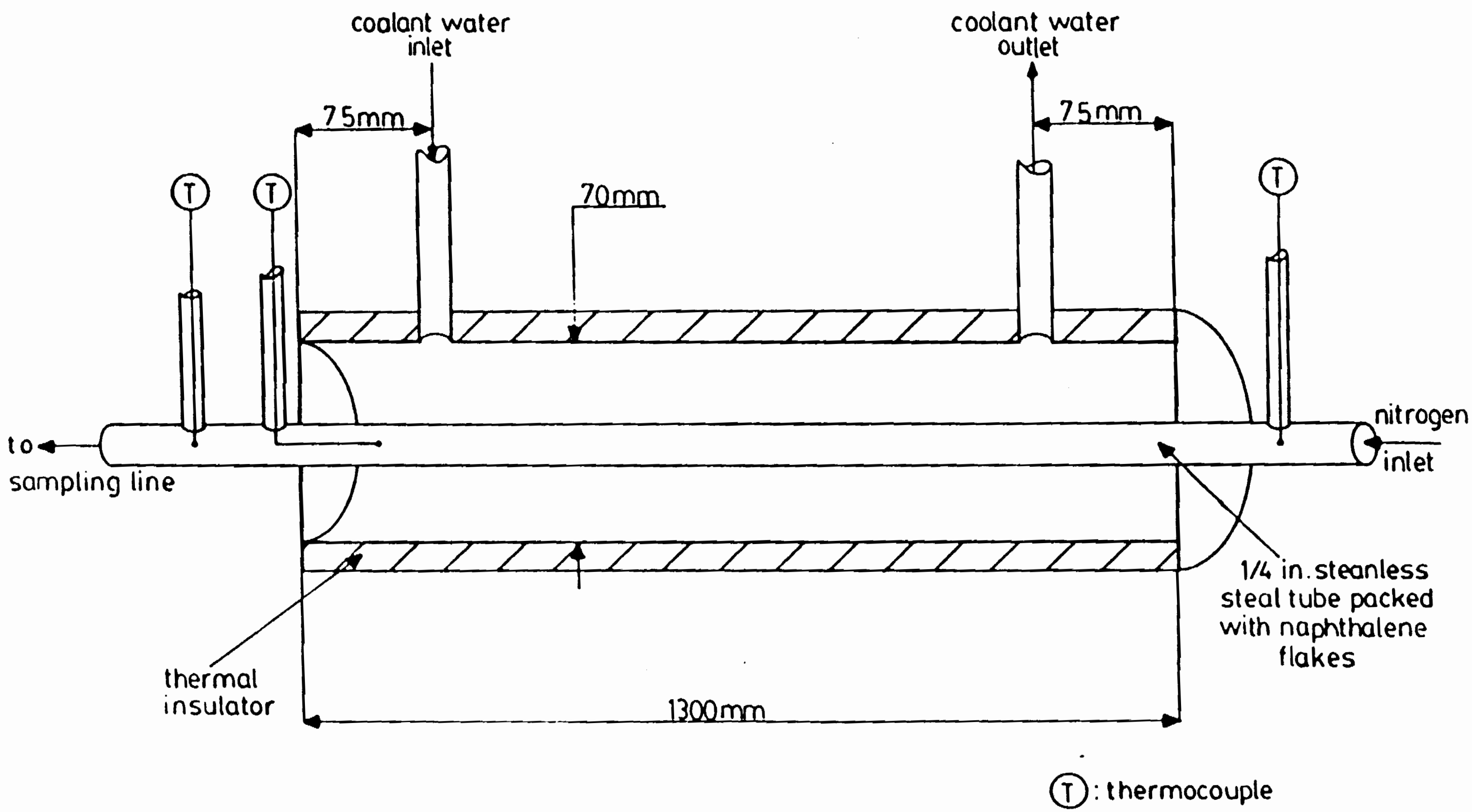


Figure 10. Naphthalene saturator: the drawing shows the saturator filled with naphthalene flakes and placed inside a water heat exchanger.

2.4.2 Experimental Procedure and Results

A steady flow of nitrogen gas is maintained through the saturator. When the heat exchanger-saturator system reaches a constant temperature, several samples of gas are taken. Figure 11, on page 34, shows two examples of chromatograms. In order to verify that the gas leaving the saturator is at saturation, gas-chromatographic determinations are repeated at sucessively decreseasing nitrogen flow rates. The saturation is taken to be achieved when the different chromatograms are identical.

We performed the experiment over a range of temperatures. Knowing the vapor pressure of naphthalene for each temperature, we can use these data to define a relation between vapor pressure and chromatographic peak area. (We have used the vapor pressure table from Lange's 8th Edition; see Appendix B, page 66). Figure 12, on page 35, gives our calibration plot: vapor pressure of naphthalene versus chromatographic peak area. All experimental data are reported in Appendix B.

The equation of the gas chromatograph calibration, using a first order linear regression, is:

$$p_n = -0.341 + 2.488 \times S$$

with a correlation coefficient of 0.998.

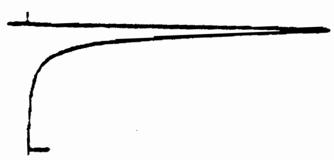
where:

p_n : partial pressure of naphthalene in the gas phase, (Pa)

S : area of the chromatographic peaks.

AREA %

RT	AREA	TYPE	AREA %
0.58	1111400	SBB	100



AREA %

RT	AREA	TYPE	AREA %
0.58	1396100	SBB	100

Figure 11. Gas chromatograms: the area of the chromatographic peaks is related to the amount of naphthalene within the saturator offgas stream.

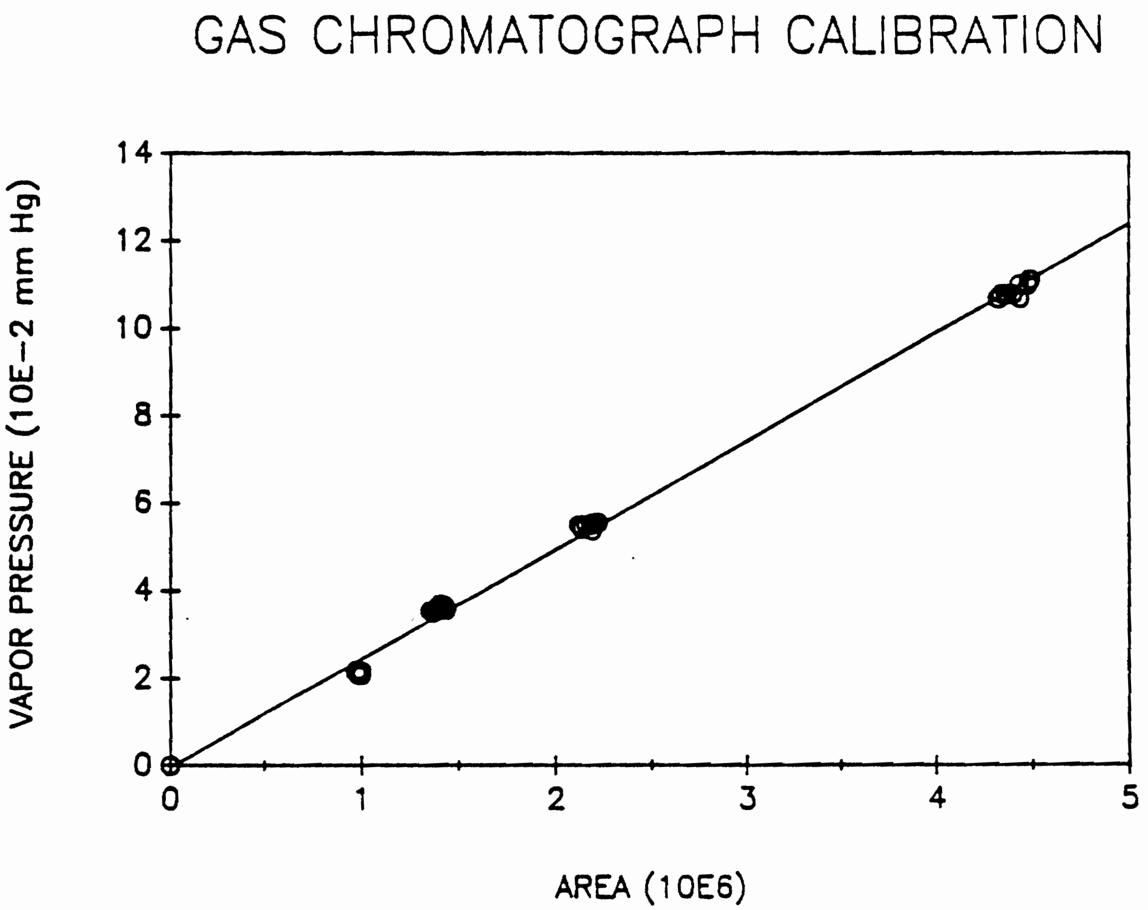


Figure 12. **Gas chromatograph calibration:** relation between the chromatograph analysis and the partial pressure of naphthalene in nitrogen.

3.0 Mass Transfer Experiments. Results and Discussion

This chapter gives a brief description of the experimental program, presents results, and comments thereupon. Effects of vibration intensity, particle size and density, and bed height have been specifically examined.

3.1 Experimental Procedure

A weighed quantity of coated beads is placed within the bed vessel and is vibrated at vibration intensities K = 4, 2, and 0. (K = 0 signifies no vibration.) For each of several rates of aeration with nitrogen, several gas chromatograph injections are performed. When several consecutive chromatograms are identical, we assume a steady state to have been achieved, and the data are retained. For most of the beads studied, aeration flow rates ranging from 0 to 40 l/min have been used. Between two different rates of aeration, the sampling line and the sampling loop are swept clean by a stream of pure nitrogen. When, for the same aeration and vibration intensity, areas of consecutive chromatograms are seen to be decreasing, we take it that naphthalene loss from the beads has become so great that bare surfaces are developing upon the beads. We then replace the bed with fresh, coated particles. We experienced this phenomenon often in work at small bed depths, where the mass transfer is intense.

All of the experiments have been conducted using beds with horizontal top surfaces and homogeneous distributions of beads in the vessel. Two different bed heights were used: 24 mm and 1 mm — the latter being termed an ultra-shallow bed.

All the experimental results are given in Appendix C, Tables 6 to 38. Figures 30 to 40 display the results in form of plots of Sherwood versus Reynolds Number.

These dimensionless numbers are calculated as shown in Section 1.3. The temperature of the gas leaving the aerated vibrated bed determines the saturation pressure $p_{n,sat}$; see the vapor pressure table of naphthalene (Appendix B, on page 66). The partial pressure of naphthalene within the offgas stream is determined by means of the gas chromatograph calibration plot (Figure 12 on page 35).

Since a chromatogram is sensitive to the conditions at which the gas chromatograph is working, we have maintained constant operating conditions. The flow rate of carrier gas (nitrogen) as well as the flow rates of air and hydrogen used for the Flame Ionization Detector of the gas chromatograph are checked before starting each experiment.

3.2 Effect of Vibration Intensity

The general trend to be expected is that the mass transfer process increases with increasing vibration intensity. Vibration agitates the particles of the bed. Therefore, the more the particle bed is vibrated, the more solid mixing occurs.

Since aerated vibrated bed behavior is different at a depth of 1 mm from that at 24 mm, it is important to consider the two cases separately.

Thomas *et al.* (1989) have studied the different states exhibited by shallow and ultra-shallow vibrated beds. They describe two different states: a "coherent-expanded (C-E) state," in which the particles form a turbulent disperse shallow layer; and a "coherent-condensed (C-C) state," in which particles move together in a condensed layer. For a given particle, the transition from C-E state to C-C state is sharp and has been quantified as a function of vibration intensity and bed depth, where the latter is expressed as the number of particle layers. For a 1-mm bed, an important factor controlling mass transfer may be whether the bed displays the C-E or C-C state.

Figure 13, on page 39, gives mass transfer data for a small particle size, -100+140 Master Beads, at a depth of 1 mm. A line through the points for K=2 is amost identical to one for K=0. whereas the K=4 line is well above the two other lines. According to Thomas *et al.* (1989), at K=2 a 1-mm bed of these particles displays the condensed C-C state. The bed has a relatively low porosity and displays a bulk-circulation pattern. Solid mixing is small, and the physical situation is such that the bed at K=2 displays a mass transfer process essentially indistinguishable from that seen in a conventional fluid bed (K=0). In contrast, at K=4 the bed is in the expanded C-E state, where intense particle motion enhances the relative velocity between particles and gas, increasing naphthalene sublimation by mass transfer.

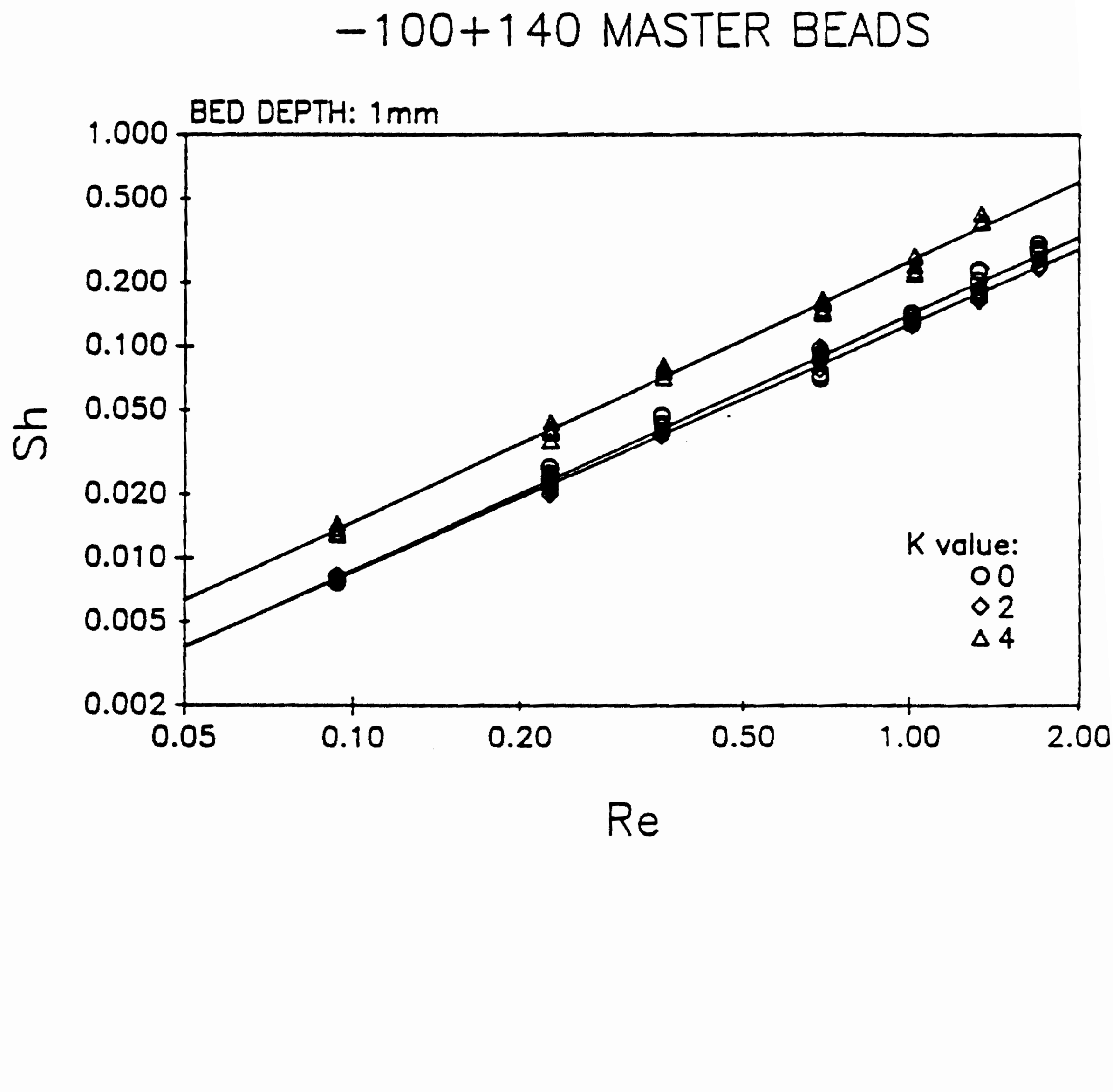


Figure 13. Effect of vibration intensity on small particles: the vibration effect is only noticeable at K = 4, when the bed is expanded. At K = 2, the bed is condensed, almost no effect is seen.

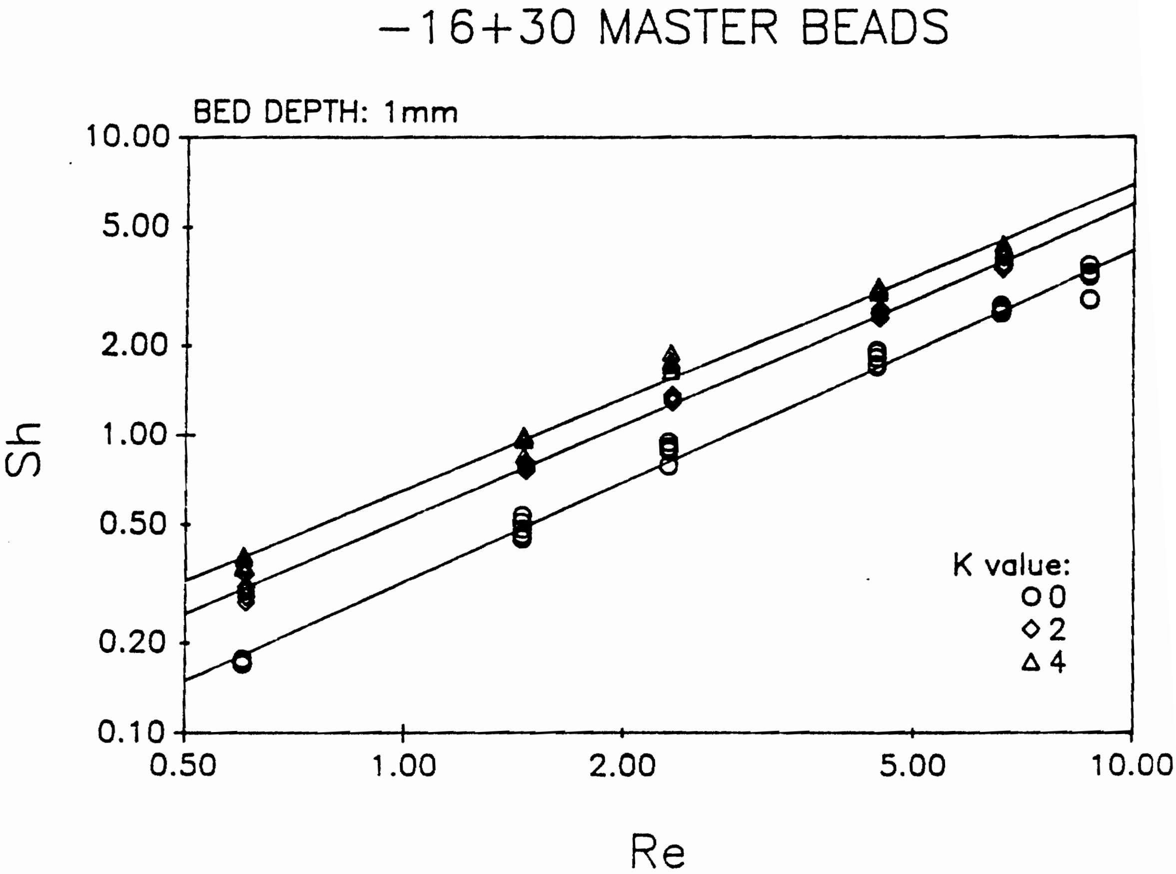


Figure 14. Effect of vibration intensity on big particles: the vibration effect is already important at K = 2, the bed being expanded earlier for this particle size.

Figure 14, on page 40, gives data for a large particle size, -16+30 Master Beads. At this size, a 1-mm bed is in the expanded C-E state at K=2 as well as at K=4. Therefore, the difference in mass transfer between these two vibration intensities is less pronounced than for the smaller particles. At both intensities, mass transfer is enhanced in respect to the non-vibrated fluid bed (K=0).

For low-density glass beads, the difference between the two states is less pronounced, (compare Figure 13 with Figure 15 on page 42). The bed vessel was composed of plexiglas, and a strong static electricity effect occurred in beds of glass beads. The particles, attracted to one another, tended to form clusters or to stick to the vessel wall, decreasing the vibration effect.

At a depth of 24 mm, a vibrated bed always displays the C-C state. That is to say, the particles remain compacted and move in concert, acting as a coherent mass. Mixing of the naphthalene particles does not increase substantially with increasing vibration intensity. The mass transfer process is scarcely affected by the vibrations. This can be seen by superimposing Figures 16, 17, and 18. Experimental data points are not shown in these plots, as well as in most of the following figures. The two points at the extremes of the lines given in the figures represent only the limits of investigation.

In Figures 19 and 20 show results from previous investigations on fluidized beds (K = 0). All plots have the same trend: they are almost parallel, but our results are, most of the time, below the data found in the literature. It is important to recall that results obtained by Resnick and White correspond to their investigation on naphthalene sublimation using a stream of air in a bed 12.7 mm in height and 31 mm in diameter. It is difficult to make a definitive comparison with our data, since Resnick and White's experimental conditions are not similar to those used in the present study. Nevertheless, an experiment, using the same bed depth as Resnick and White's investigation, has been

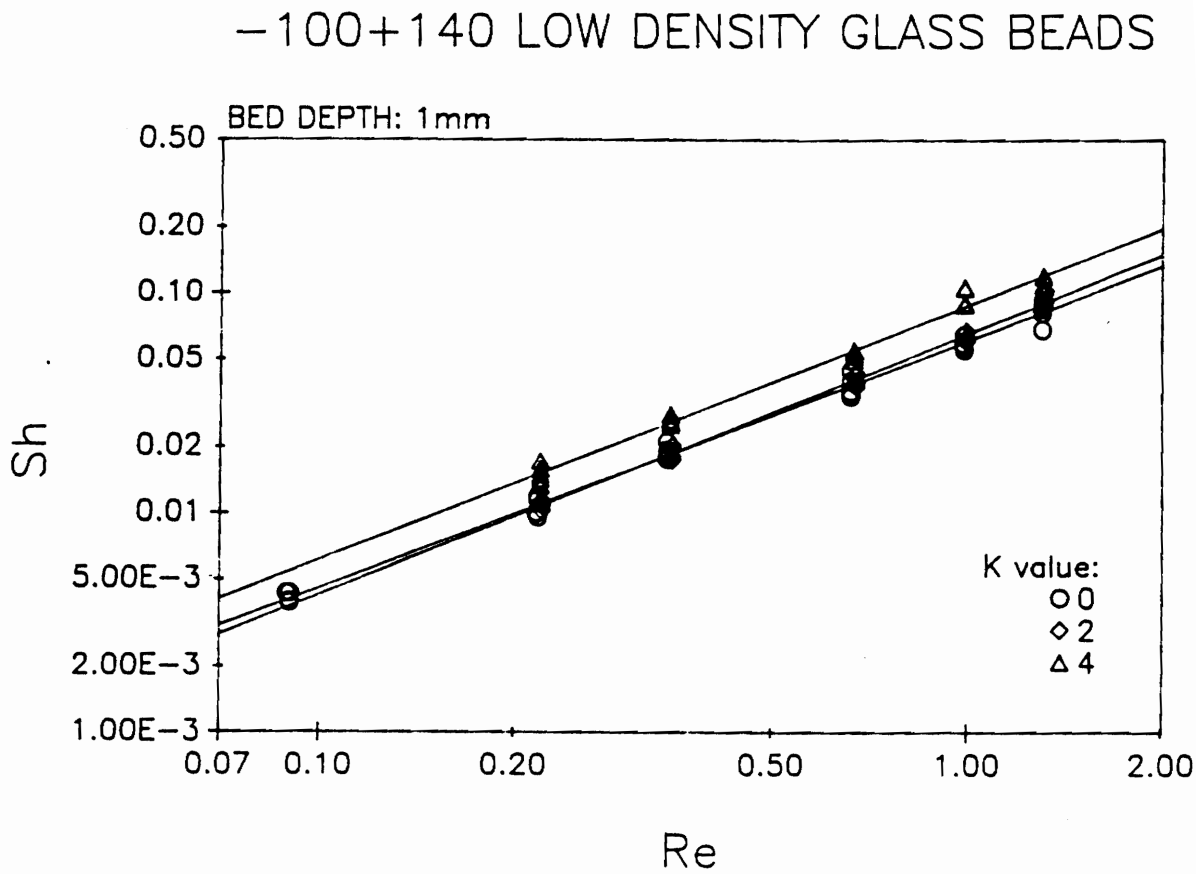


Figure 15. Effect of vibration intensity on small, low density glass beads: the vibration effect is less pronounced than for the -100+140 Master Beads.

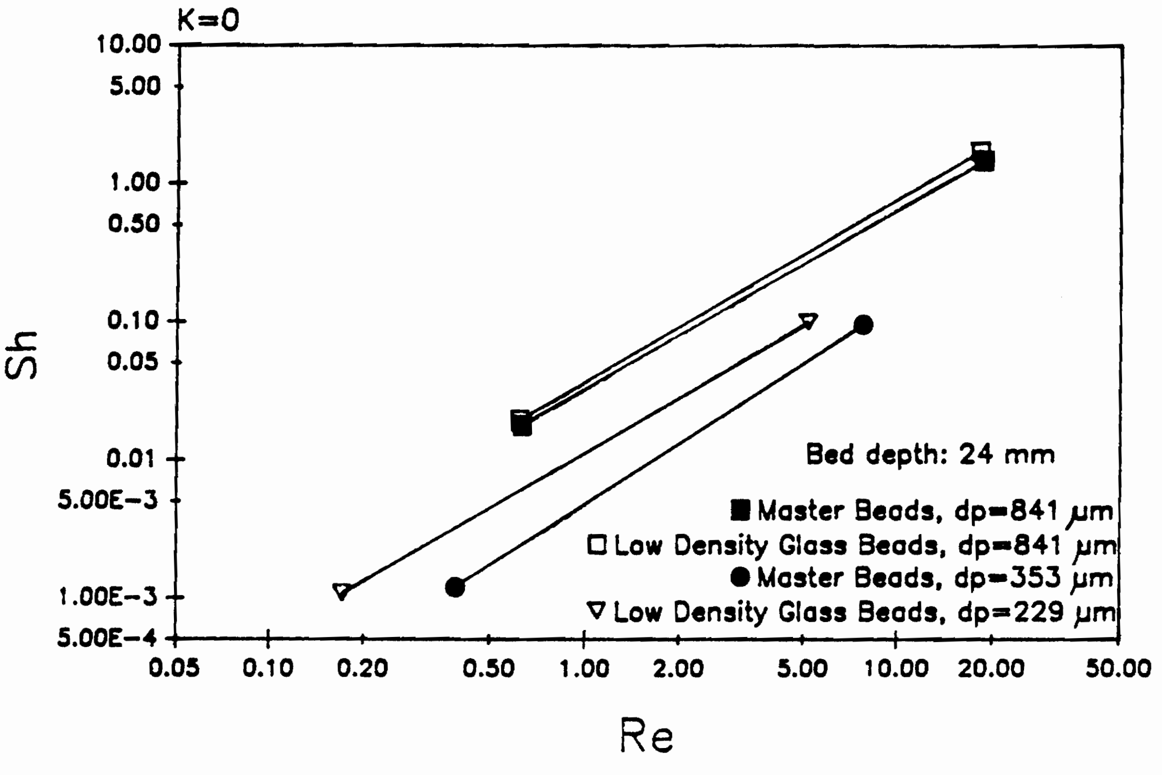


Figure 16. Mass transfer results at K = 0 (bed depth 24 mm).

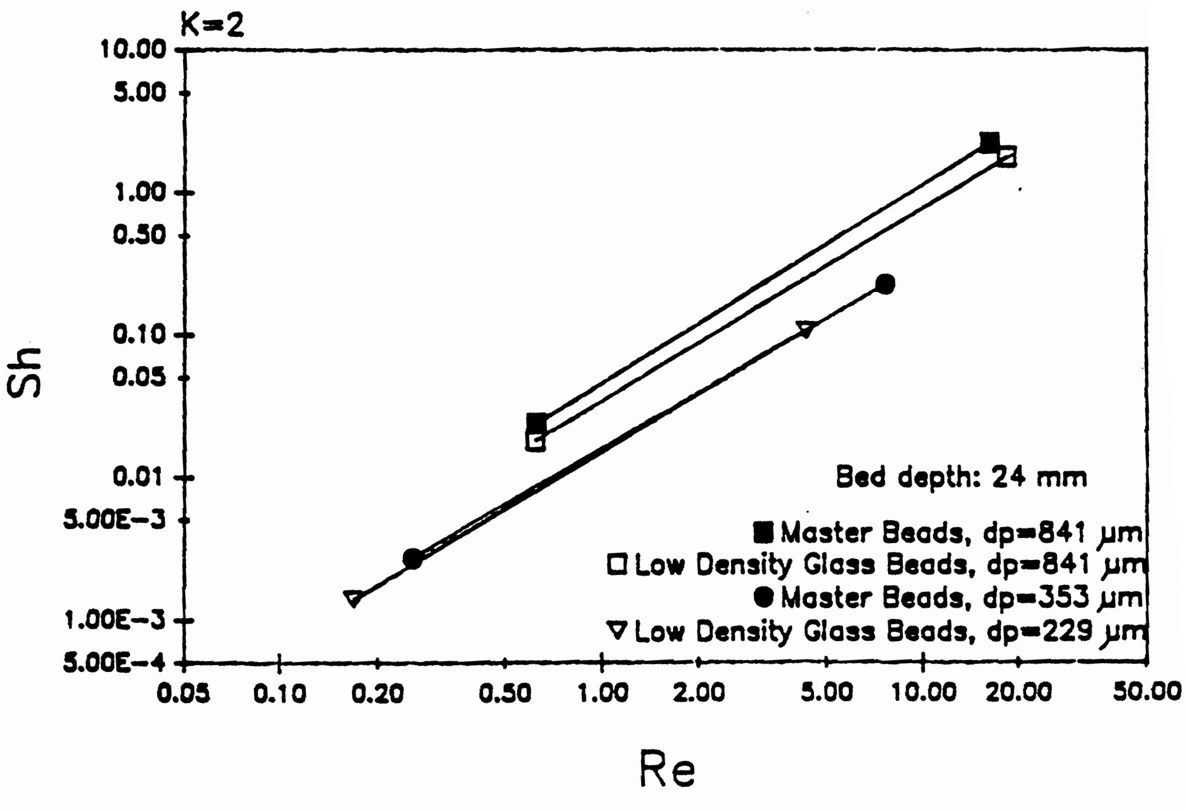


Figure 17. **Mass transfer results at K = 2 (bed depth 24 mm):** compared with K = 0; a small increase in mass transfer is noticeable.

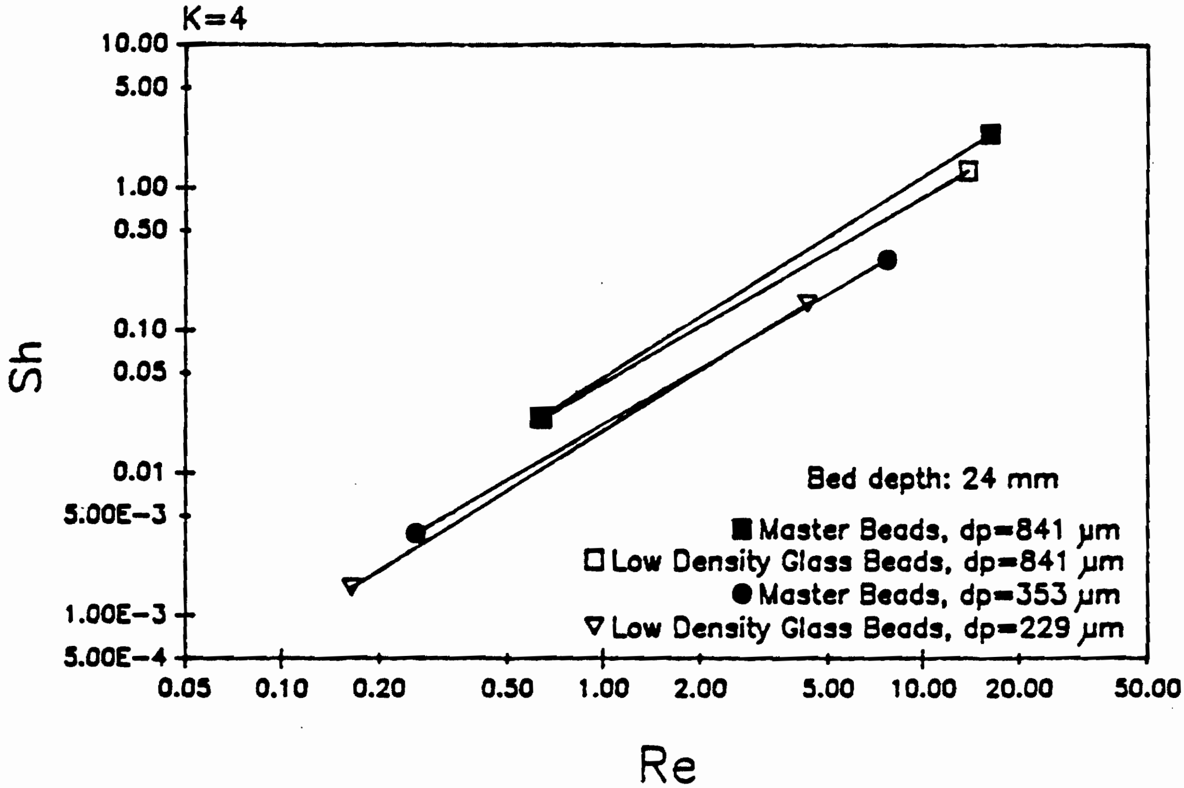


Figure 18. Mass transfer results at K = 4 (bed depth 24 mm): increase in vibration intensity (from K = 2 to K = 4) slightly affects the mass transfer process.

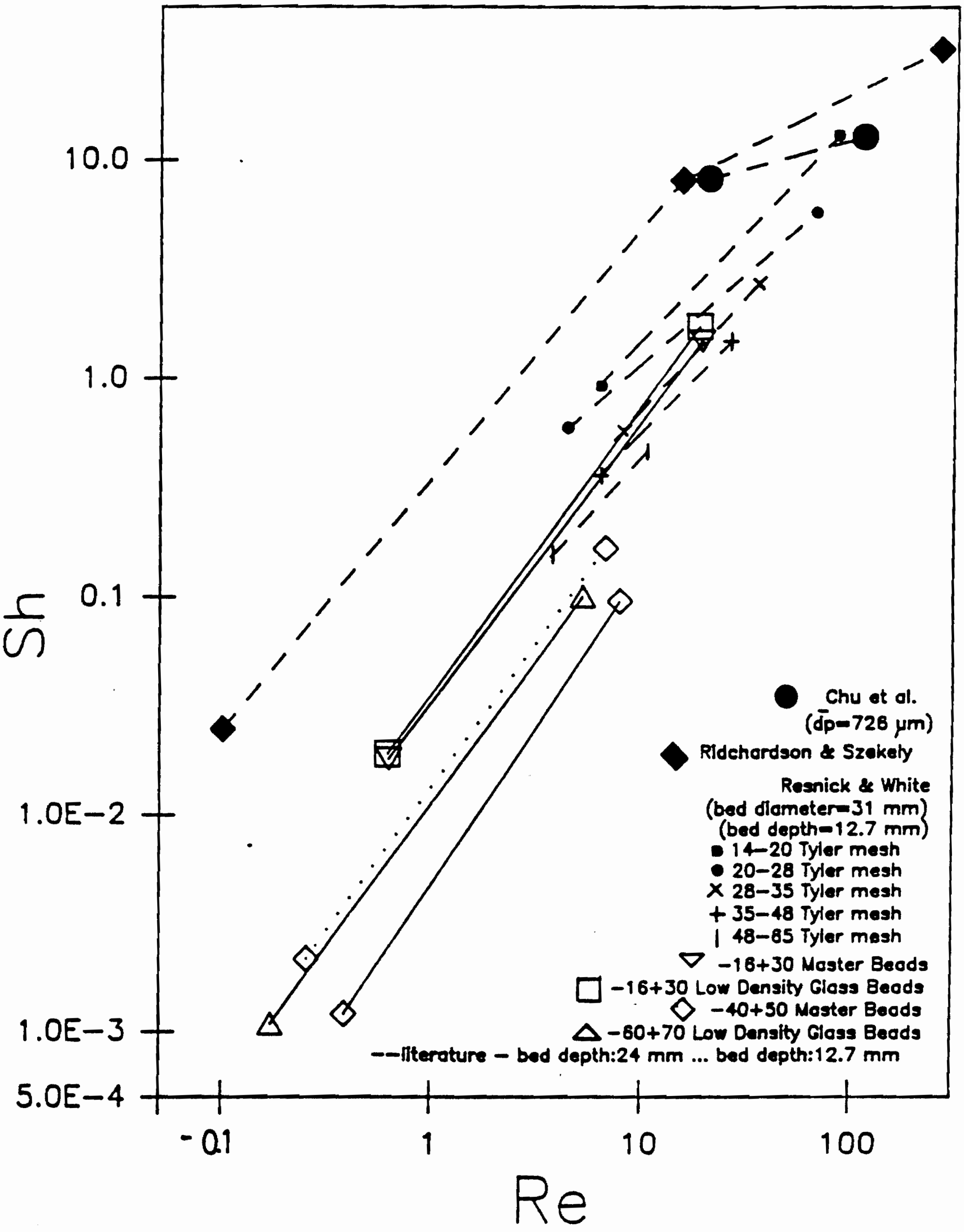


Figure 19. **Mass transfer results at K = 0, (bed depth 24 mm):** comparison with the literature on fluidized beds. Results from Richardson and Szekely's experiment using a $5d_p$ bed depth are also drawn, showing the upper mass transfer limit.

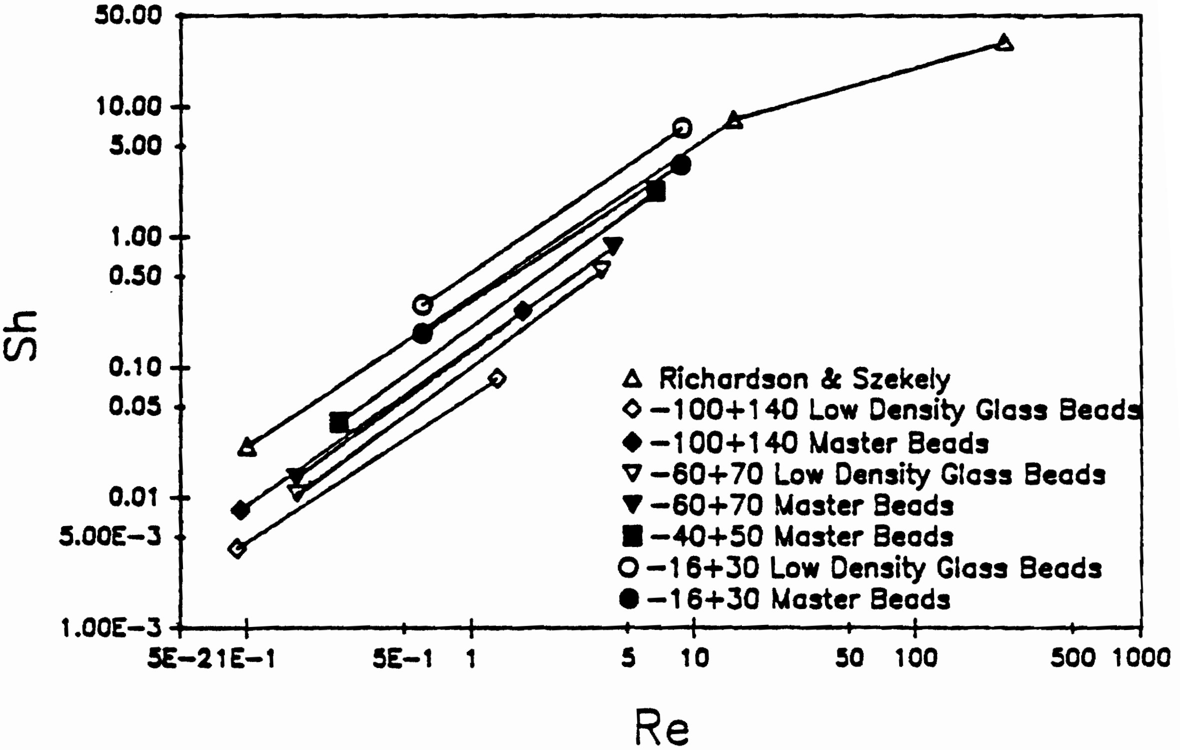


Figure 20. Mass transfer results at K=0, (bed depth 1 mm): comparison with Richardson and Szekely experiment with a $5d_p$ bed depth.

conducted and shows that the disparity of our results is partially due to a bed height difference. This experiment is described in Section 3.4, on page 53.

Figure 20 compares our results for a 1-mm bed with those of Richardson and Szekely at bed depths amounting to five particle diameters. A limitation on the range of the variables that has been accessible for this study has prevented our reaching the level of Reynolds Number at which Richardson and Szekely noted a sharp change in slope.

Moreover, we have not seen a change of trend when the aeration rate increased from below to above the minimum fluidization velocity of the particles. (Appendix D provides pressure drop measurements and minimum fluidization velocities of the beads.)

3.3 Effect of Particle Size and Density

The literature reports a trend toward increasing Sherwood Numbers with increasing particle size. We do not find that vibration alters this trend. Figures 21 and 22, on pages 49 and 50, illustrate the trend for K = 2, with bed height of 24 mm and 1 mm, respectively. Figures 23 and 24, on pages 51 and 52, display similar results at K = 4.

Although the contacting surface of the bed increases with decreasing particle size (for the same bed height), the mass transfer process is poor for small particles. It is well known that the efficiency of solid-gas contacting is strongly dependent to the characteristics and behaviors of the particles in motion. Most of the particles that we studied belong to the same group of powders, Group B; -16 + 30 mesh beads are just at the B-D group boundary. Nevertheless, our particles behave differently according to their size, density, and cohesiveness. Small particles are subject to interparticle forces that increase

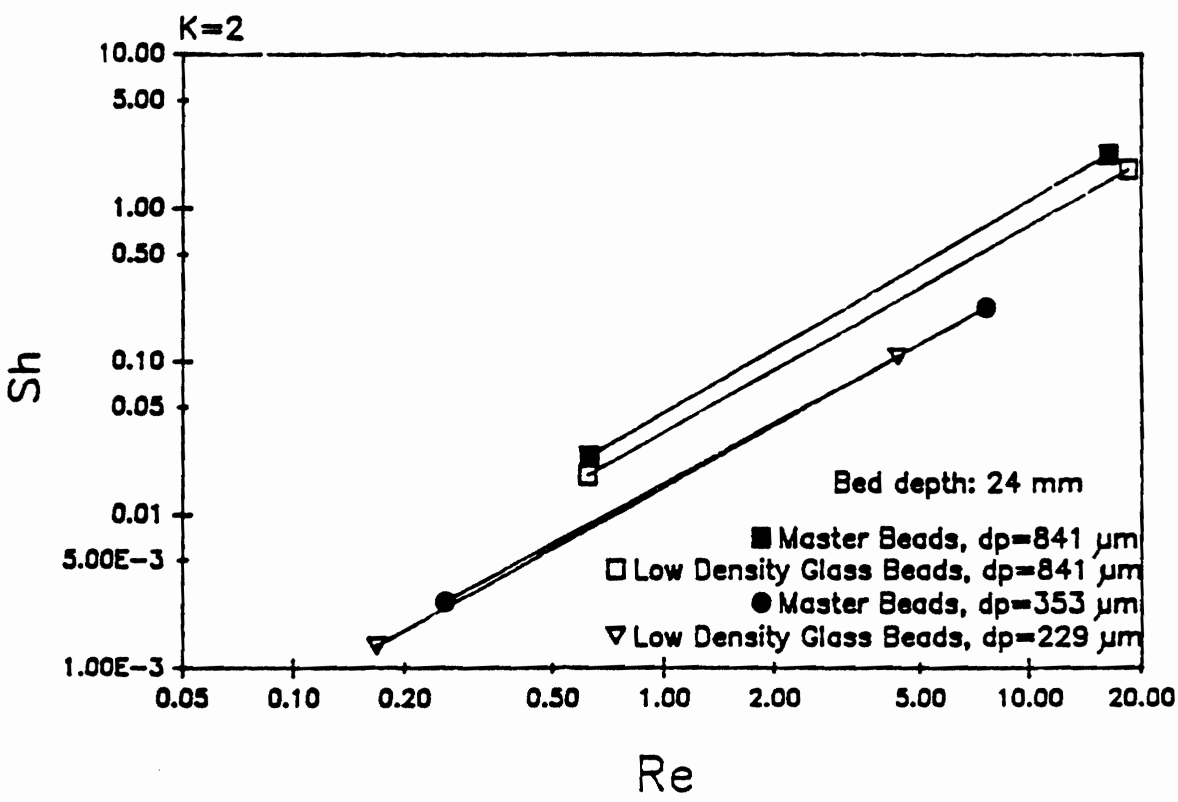


Figure 21. Effect of particle size and density; K = 2, bed depth = 24 mm: the mass transfer increases as the particle size and the density increase.

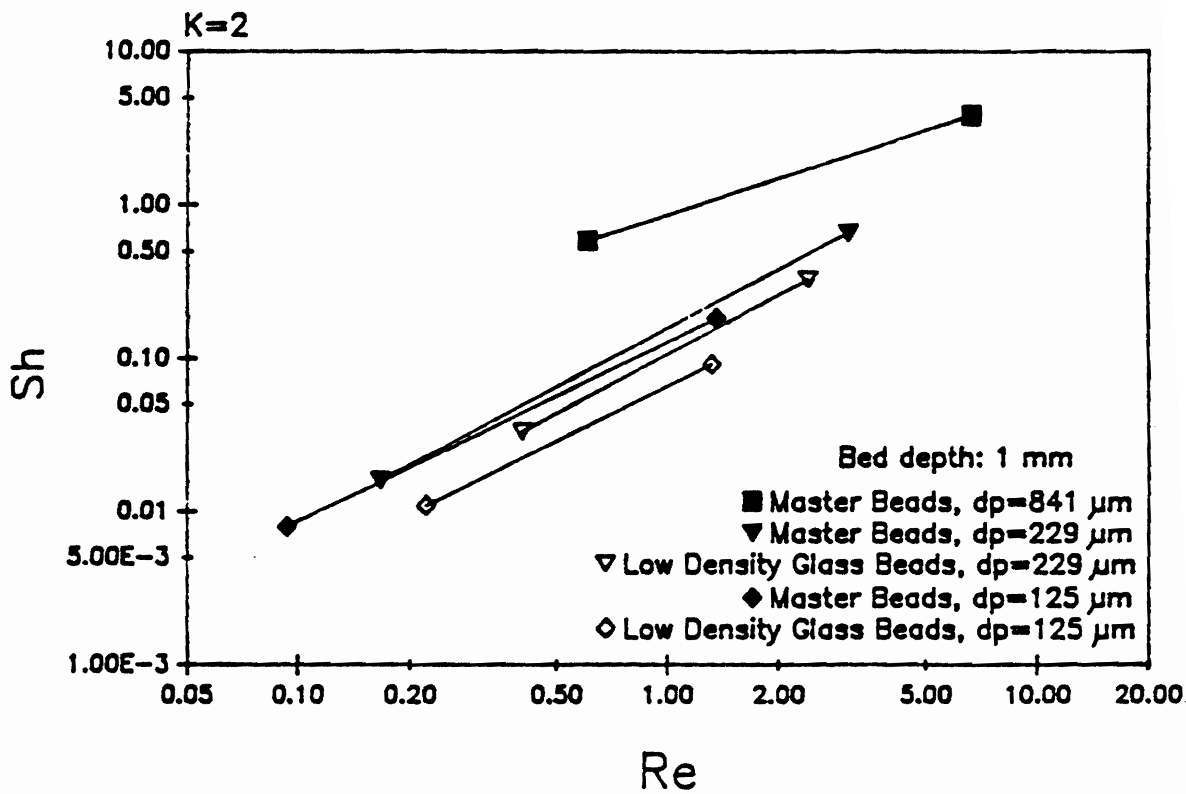


Figure 22. Effect of particle size and density; K = 2, bed depth = 1 mm.

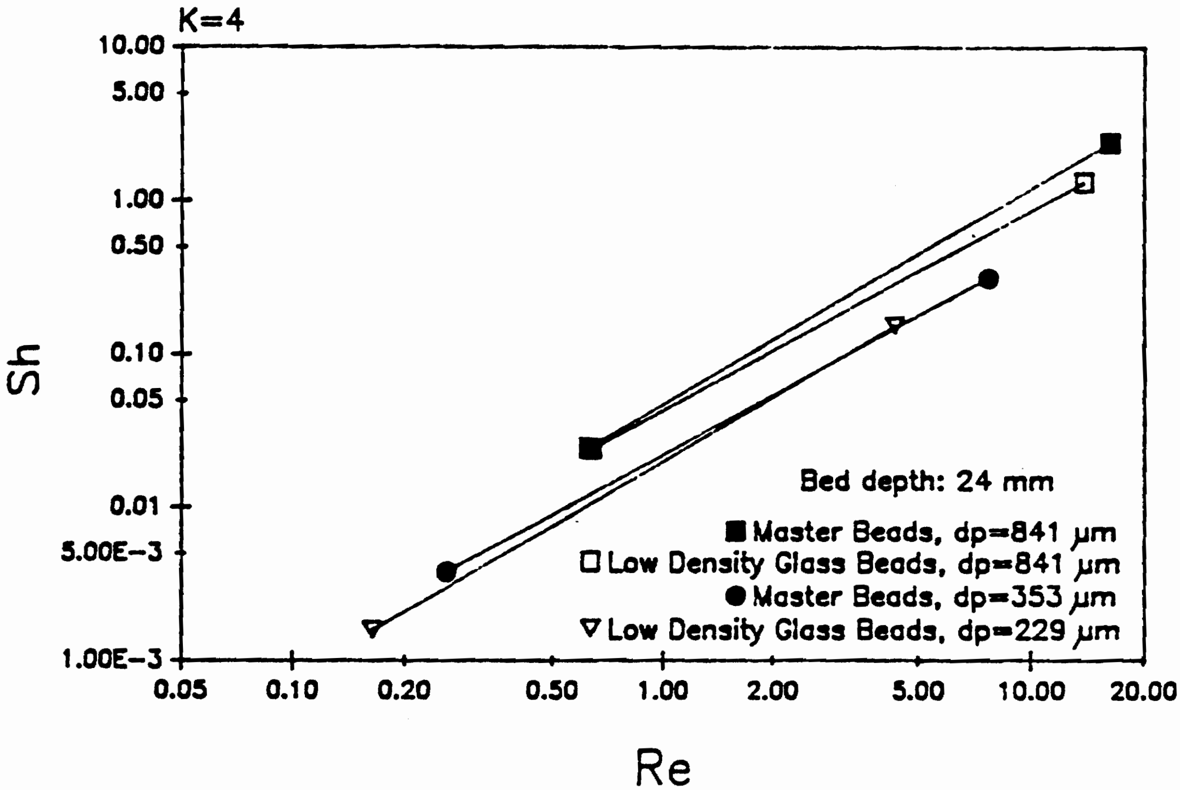


Figure 23. Effect of particle size and density; K = 4, bed depth = 24 mm.

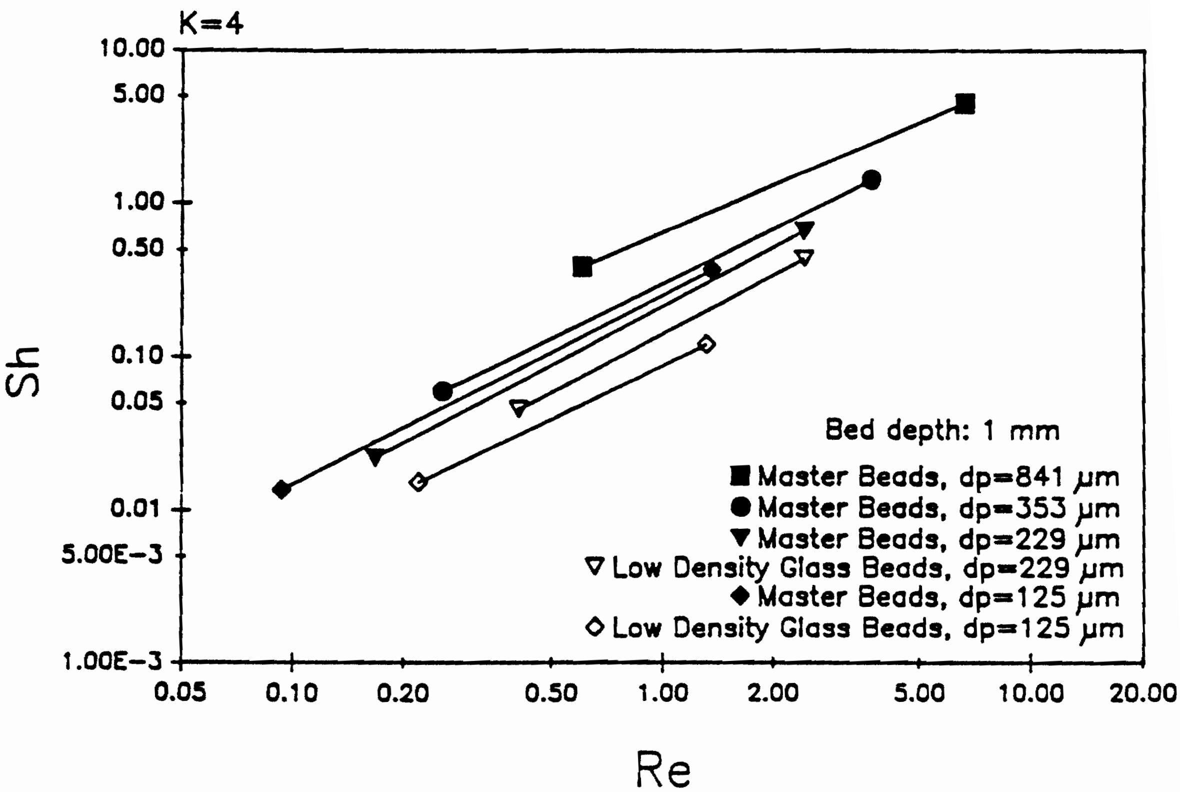


Figure 24. Effect of particle size and density; K = 4, bed depth = 1 mm.

as size decreases. Agglomeration of smaller particles tends to reduce their effective contacting surface and to increase gas by-passing. It is not surprising that mass transfer rate decreases with particle size.

Unlike Chu *et al.*'s observation, we notice an effect of density on the mass transfer coefficient. The Sherwood Number increases with increasing density. Nevertheless, we do not know whether this result is a density effect or a static electricity effect. As described in the previous section, low density glass beads are very sensitive to static electricity forces that develop within the bed. The beads tend to stick to the vessel wall or to form clusters. The motion of the beads becomes less turbulent, and this alteration in behavior is a credible reason for a decrease in effectiveness of naphthalene sublimation.

3.4 Effect of Bed Height

The experiments have been conducted with two different bed heights: 24 mm and 1 mm. Figures 25, 26, and 27 show, at K = 4 and 2, the effect of bed heights for three different particles.

As explained in the analysis of the vibration intensity effect, the difference between a 24-mm bed and a 1-mm bed is due to the change of bed state. At an ultra-shallow depth, the bed is either in a coherent-expanded (C-E) state or coherent-condensed (C-C) state, depending on the size of the particles and the vibration intensity. Bed expansion is greater and solid mixing is more intense in the C-E than in the C-C state, and this fact explains the higher mass transfer seen in some of our data in 1-mm beds. Even when a 1-mm bed displays the C-C state, its expansion and mixing are more intense than in a 24-mm bed. Accordingly, mass transfer at 1-mm depth, even in the C-C state can be

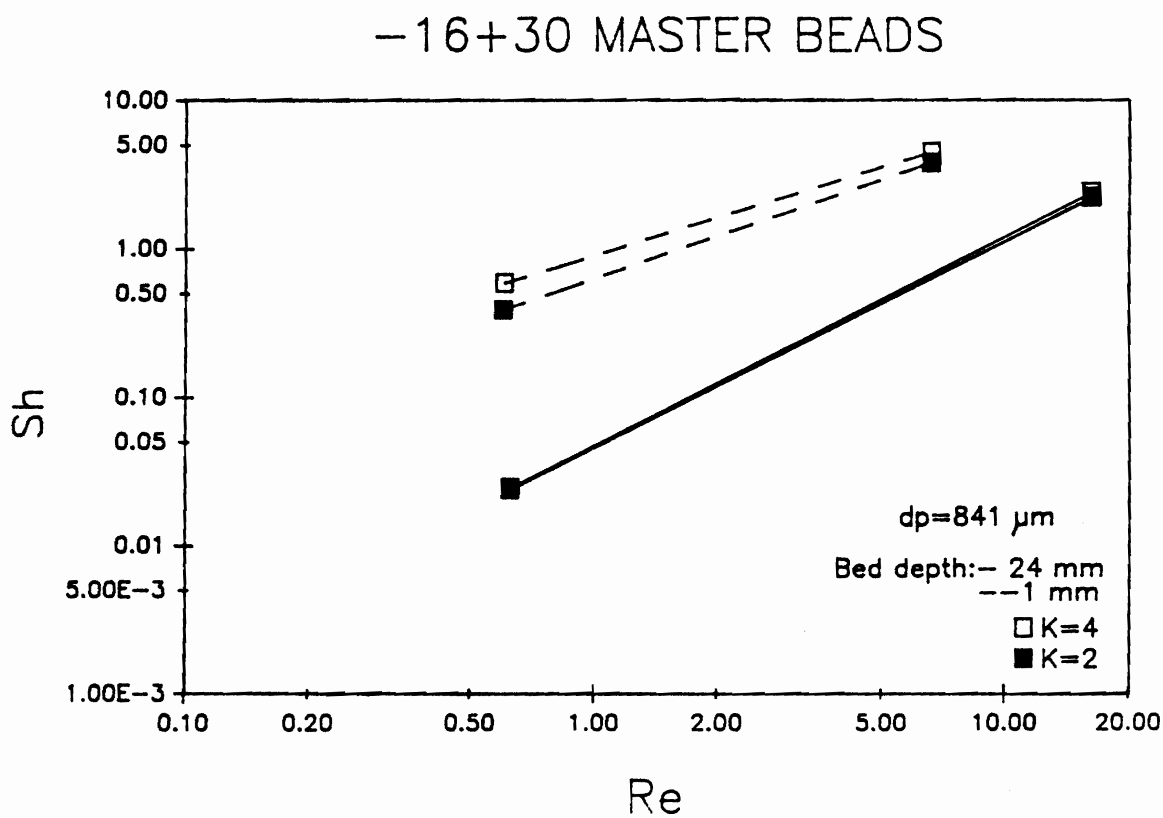


Figure 25. Effect of bed height; -16+30 Master Beads, K=4 and 2.

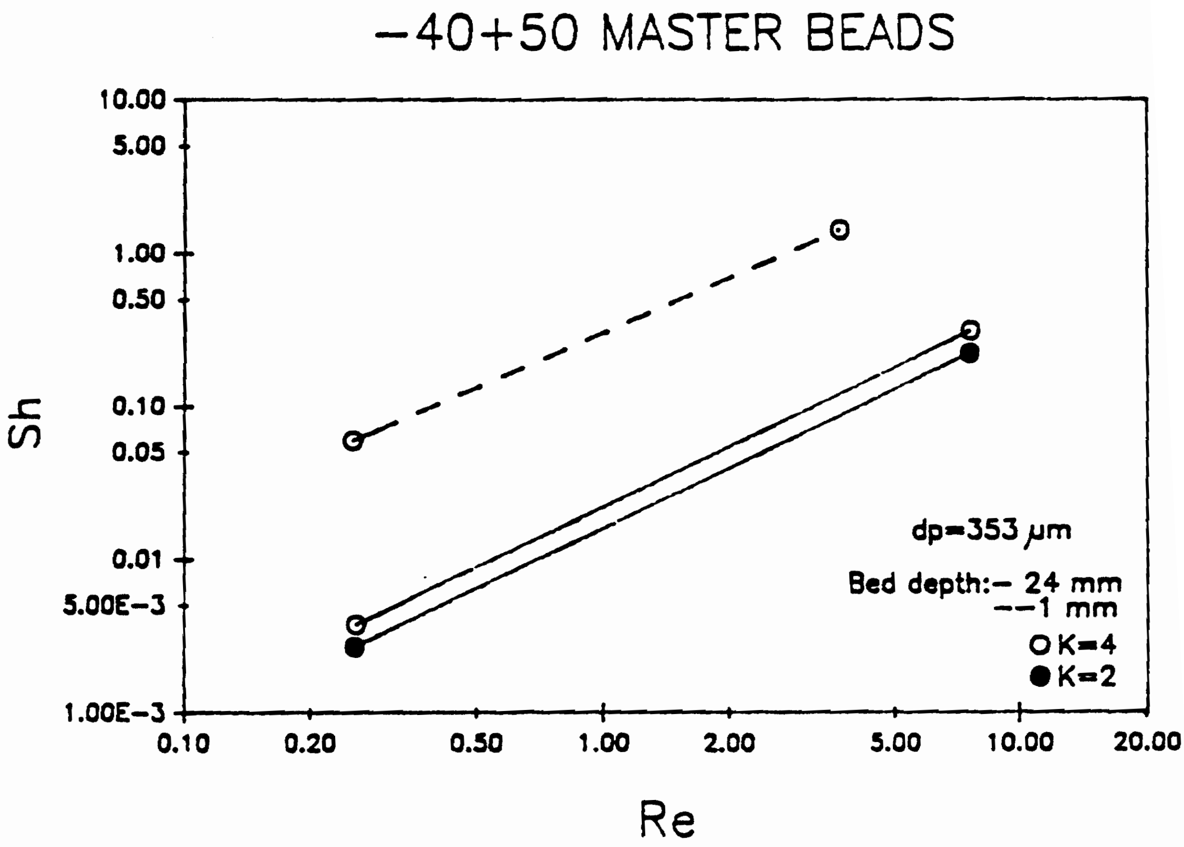


Figure 26. Effect of bed height; -40 + 50 Master Beads, K = 4 and 2.

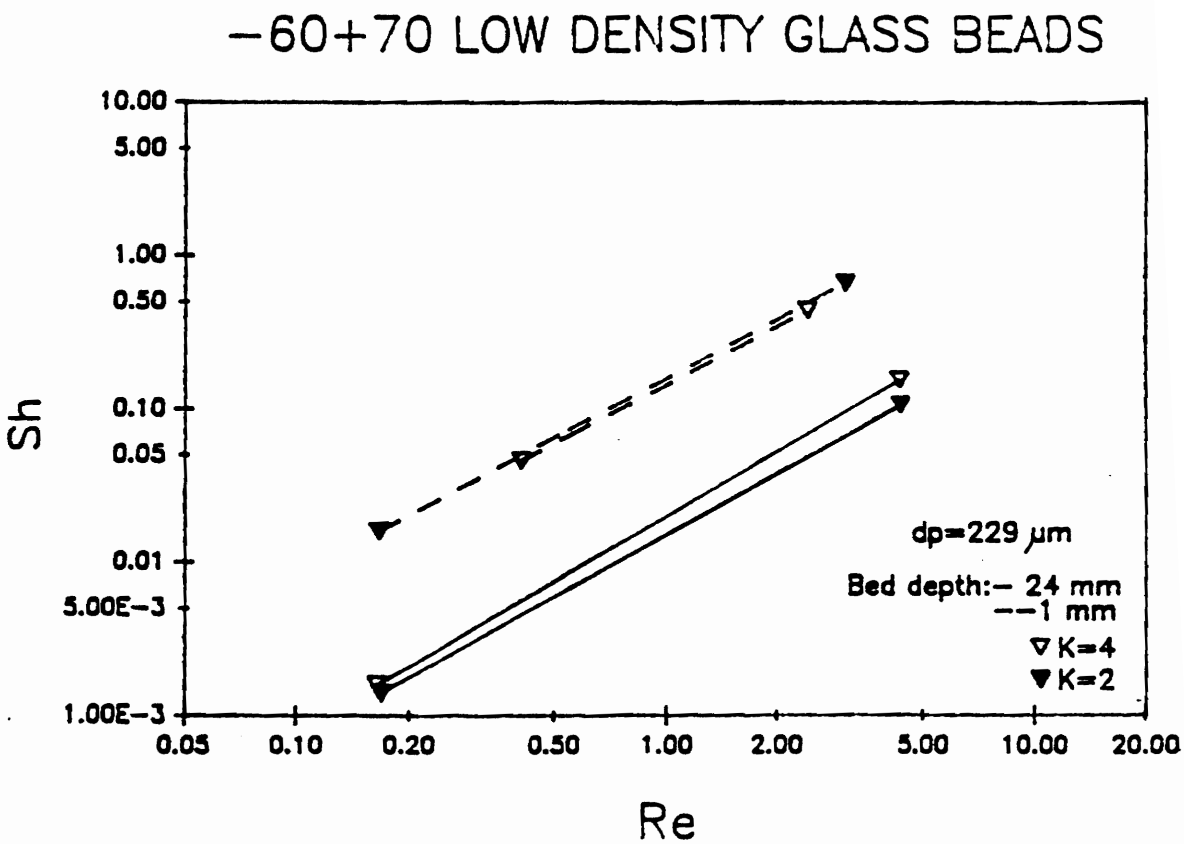


Figure 27. Effect of bed height; -60 + 70 low density glass beads, K = 4 and 2.

expected to exceed that at 24 mm. The deeper bed behaves as a single mass, with little expansion, and mass transfer rate is poor.

An illustration of the strong mass transfer rate occurring in ultra-shallow beds is given in Figure 28 on page 58. It has not been possible to obtain relevant results with the -16+30 low density glass beads for an aeration flow rate higher than 10 l/min when vibrating at an intensity of K=4. Naphthalene sublimed so quickly that its concentration in fluidizing nitrogen fell dramatically from one analysis to the next. In the figure, this phenomenon accounts for the curvature of the plot at Re > 5.

Our results also show an increase of mass transfer with decreasing bed height for a fluid bed (K=0). Resnick and White concluded that this phenomenon not did not occur in a fluid bed. We have, however, established the phenomenon in an experiment using a third bed height of 12.7 mm, identical to that used by Resnick and White. Figure 29, on page 59, shows, for -40+50 Master Beads, the increase of mass transfer rate when the bed height decreases.

The increase in Sherwood Number is less marked between 12.7 mm and 24 mm than between 1 mm and 12.7 mm bed heights. Behaviors of 24-mm and 12.7-mm beds being similar, the improvement in mass transfer rate at 12.7 mm, compare to the 24-mm bed, is less obvious than at 1 mm. Resnick and White's conclusion on the effect of bed height (see Figure 6 on page 16) may be doubtful, since they give only a few points for their 25.4-mm bed height. Moreover, these data are a little below results from their 12.7-mm bed, a fact that contradicts their stated conclusion.

Taking into consideration the influence of bed height on mass transfer rate, we have to reconsider the comparison, sketched in Section 3.2, of our results with the literature. In Figure 19, on page 46, a dotted line gives our result for -40+50 Master Beads using a bed height of 12.7 mm. We notice, as previously, the increase of the mass transfer rate from the 24-mm bed to the 12.7-mm bed. Although the results at 12.7-mm depth are

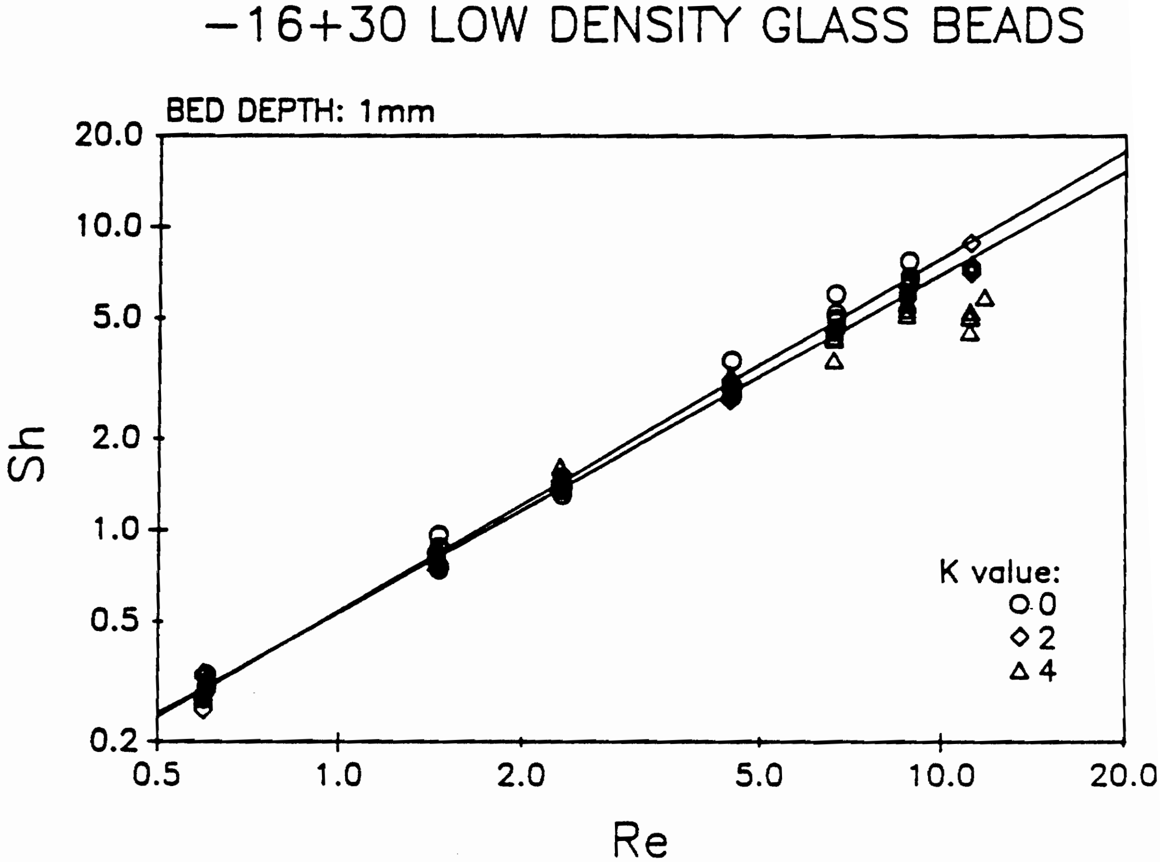


Figure 28. **-16 + 30 low density glass beads; bed depth = 1 mm:** at K = 4, the naphthalene loss is so important that, from one measurement to another, the naphthalene concentration decreases.

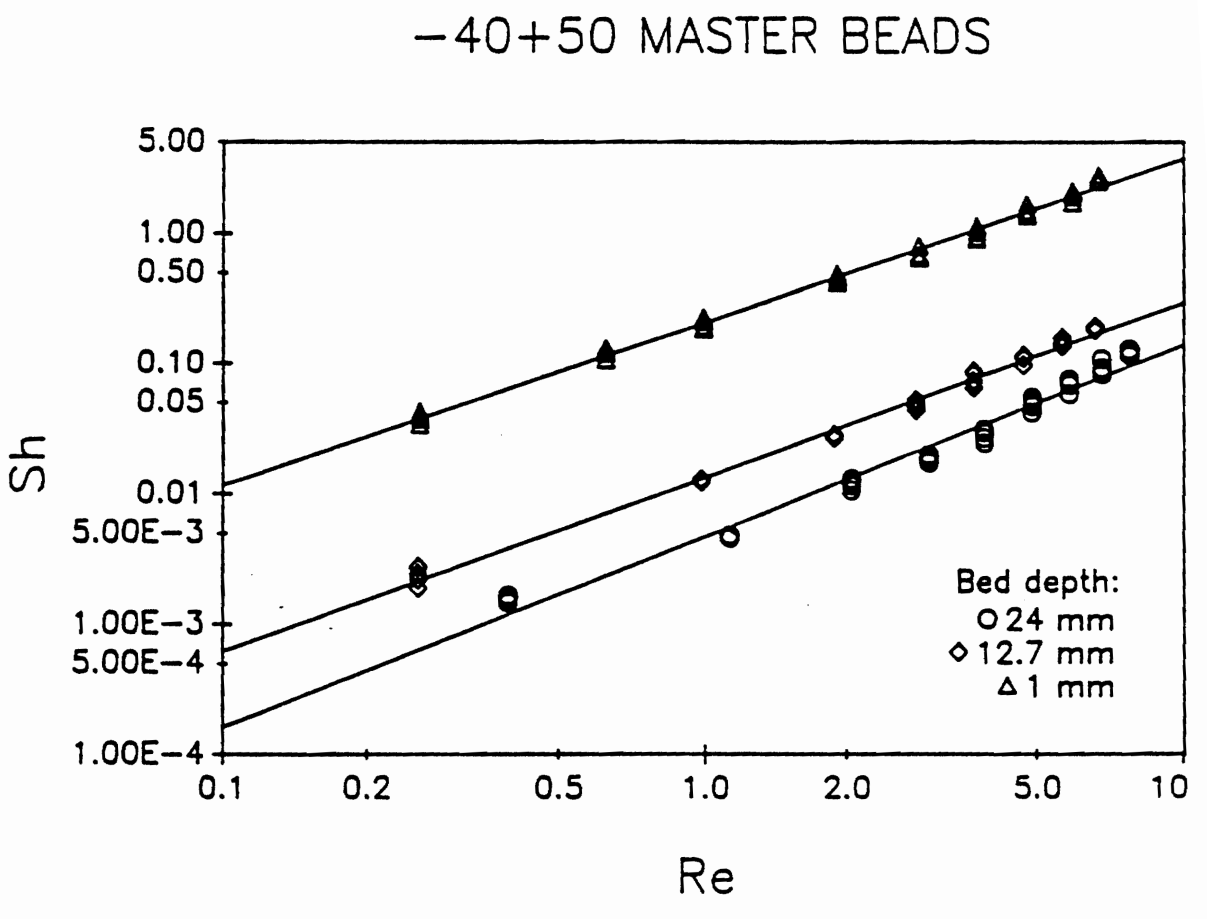


Figure 29. Effect of bed height on mass transfer at K = 0.

now closer to Resnick and White's experiments, they are still lower, which may represent effects of particle characteristics and fluidizing gas, and as well, of course, to differences in experimental method.

4.0 Conclusion

Mass transfer coefficients were measured in a cylindrical aerated vibrated bed in which naphthalene-coated beads were sublimed by nitrogen gas. Two kinds of coated beads of different density were used: Master Beàds and low-density glass beads. A wide range of solid particles, from 125 to 841 μm of geometric mean size, were studied. The particle bed was vibrated at a frequency of 25 Hz and using vibration intensities of 0, 2, and 4. The investigation was conducting using bed depths of 24 mm, 1 mm (ultra-shallow), and, in a limited amount of work, 12.7 mm. The fluidizing gas flow rate was varied from 1 to 40 l/min. Analysis of the gas leaving the bed was made by means of a gas chromatograph, giving the concentration of sublimed naphthalene in the nitrogen gas stream.

Using the dimensionless representation Sherwood number versus Reynolds number, we noticed that:

- In general, the vibrations, by inducing a strong particle circulation within the bed vessel, increase the mass transfer rate to some extent. Nevertheless, depending on the height of the bed, the effect of vibrations can differ. For ultra-shallow beds, the factor controlling the mass transfer is the state of the bed. In the coherent-condensed state, where the bed exhibits a bulk-circulation pattern and has a low porosity, the vibrations scarcely improve the mass transfer rate. When, by increasing the vibrational intensity, the bed exhibits the coherent-expanded state, a strong solid mixing and motion occure which increase the mass transfer rate. Deeper beds behave more like a coherent mass, and solid mixing does not increase apprecially with the vibration. The increase of the mass transfer process is, in this case, almost insignificant.

• The Sherwood number increases with increasing particle size as well as density, whether the bed is vibrated or not. Nevertheless, we might suppose the effect of density that we have seen to be a result of static electricity forces which appeared in our beds of low-density glass beads. These particles tend to stick together or at the vessel wall, reducing the solid mixing, and thus the mass transfer process.

• The mass transfer is also affected by the bed height; the Sherwood number increases with decreasing bed depth. Since the appearance of shallow or ultra-shallow beds is more turbulent than for deep beds, an improvement of the mass transfer rate is not surprising.

According to these considerations, only shallow, aerated vibrated beds may be an interesting device for processes where good mass transfer is needed. Use of vibrations as a means for improving the mass transfer rate in deep beds does not appear advantageous.

5.0 Bibliography

Bachmann, D., *Verfahrenstechnick Z.V.D.I. Beiheft*, No.2 (1940),43. Cited in Gutman,(1974).

Cheah, C.W., *Heat Transfer between a Supernatant Gas and a Flowing Vibrofluidized Bed of Solid Particles*, M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, (1986).

Chlenov, V.A., and Mikhailov, N.V., *Inzh. Fiz. Zh.*, 9, (1965),196.

Chu, J.C., Kalil, J., and Wetteroth, W.A., *Chemical Engineering Progress*,49,(1953),141.

Danielsen, S., and Hovmand, S., *Drying'80, vol.1: Developments in Drying*, A.S. Mujumdar, ed. Hemisphere Publishing Co., Washington , D.C.,(1980),194.

Ergun, S., *Chemical Engineering Progress*,48,(1952),89.

Geldart, D., *Powder Technol.*,7,(1973),285.

Gilliland, E.R., *Industrial and Engineering Chemistry*,26, (1934),681.

Gutman, R.G., *Vibrated Beds of Powders*, Ph.D. Thesis, University of Cambridge, London, United Kingdom,(1974).

Grace, J.R., *The Canadian Journal of Chemical Engineering*, 64,(1986),353.

Jackson, R., and Judd, M.R., *Transactions Institution of Chemical Engineers.*,59,(1981),119.

Kunii, D., and Levenspiel, O., *Fluidization Engineering.*, Robert, E., Publishing Company, New York,(1969).

Pakowski, Z., Mujumdar, A.S., and Strumillo, C., *Advances in Drying Vol.3.*, Ed. Mujumdar, A.S., Hemisphere Publishing Co., Washington, D.C.,(1984),144.

Resnick, W.E., and White, R.R., *Chemical Engineering Progress*,45,(1949),377.

Richardson, J.F., and Szekely, J., *Transaction Institution of Chemical Engineers*,39,(1961),212.

Shirai, T., *Fluidized Beds*, Kagaku-Gijutsu-Sha, Kanazawa, 1958. Cited by Kunii and Levenspiel,(1969).

Sunderland, P., and Ahmed, I., *Transactions Institution of Chemical Engineers*,59,(1981),95.

Thomas, B., Mason, M.O., Liu, Y.A., and Squires, A.M., *Powder Technology*,57,(1989),267-280.

Thomas, B., Lui, Y.A., Chan, R., and Squires, A.M., *Powder Technology.*,52,(1987),77-92.

Thomas, B., *Shallow Vibrated Particulate Beds: Bed Dynamics and Heat Transfer.*, Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia,(1988).

Appendix A. Tyler Standard Designation

In Resnick and White's investigation, the particles were sized using the Tyler standard screens. In order to compare with the results of the present study, the table gives the size range corresponding to the Tyler Standard.

Table 3. Tyler Standard Designation.

Tyler Standard Mesh Size	Size Range in microns	Geometric Mean Size (microns)
14-20	841-1190	1000
20-28	595-841	707
28-35	420-595	500
35-48	297-420	353
48-65	210-297	250

Appendix B. Gas Chromatograph Calibration

Gas chromatographic calibrations were performed at different temperatures of the saturator, Table 5, on page 68. A relation between vapor pressure and chromatographic peak area was obtained using the vapor pressure table from Lange's 8^{th} Edition, Table 4, on page 67.

Table 4. Vapor pressure of naphthalene.

T (°C)	P (mmHg)
10	0.0208
11	0.0235
12	0.0263
13	0.0292
14	0.0322
15	0.0353
16	0.0385
17	0.0420
18	0.0456
19	0.0495
20	0.0537
21	0.0583
22	0.0633
23	0.0689
24	0.0751
25	0.0821
26	0.0900
27	0.0989
28	0.1089
29	0.1202
30	0.1330

Table 5. Gas Chromatograph calibration

T (^oC)	P (10E-2 mmHg)	AREA (10E6)
10.80	2.2976	0.8560
10.85	2.3112	0.8665
10.85	2.3112	0.8635
10.80	2.2976	0.8565
10.90	2.3248	0.8606
10.70	2.2705	0.8644
10.95	2.3385	0.8805
10.70	2.2705	0.8773
10.75	2.2840	0.8773
10.75	2.2840	0.8697
15.50	3.6921	1.2840
15.55	3.7084	1.2730
15.75	3.7738	1.2550
15.85	3.8067	1.2540
15.80	3.7902	1.2740
15.50	3.6921	1.2290
15.45	3.6759	1.2220
15.50	3.6921	1.2040
15.50	3.6921	1.2230
15.45	3.6759	1.2140
15.65	3.7410	1.2380
15.70	3.7574	1.2490
20.45	5.5688	1.9650
20.30	5.5009	1.9450
20.35	5.5234	1.9340
20.40	5.5460	1.9260
20.45	5.5688	2.0160
20.45	5.5688	2.0220
20.15	5.5434	1.9910
20.25	5.4785	1.9370
20.35	5.5234	1.9830
20.40	5.5460	1.9940
20.45	5.5688	1.9940
28.05	10.9456	4.0590
28.00	10.8923	4.0450
28.00	10.8923	4.0330
28.05	10.9456	4.0800
28.00	10.8923	4.1480
28.10	10.9993	4.1150
28.10	10.9993	4.0880
28.10	10.9993	4.0800
28.30	11.2171	4.1450
28.35	11.2723	4.1880
28.40	11.3280	4.2030
28.40	11.3280	4.1980

Appendix C. Experimental Results

The following tables and figures give experimental results for all the particles studied. The temperature of the bed (T_{bed}) , and of the gas (T_{gas}) as well as the nitrogen flow rate (N_2 flow), the partial pressure of the gas living the aerated vibrated bed (P_n), the mass transfer coefficient (K), the dimensionless numbers Reynolds (Re), and Sherwood (Sh) are listed for each experiment.

Table 39 on page 115 provides a synthesis of the experimental results using the j_d dimensionless parameter.

$$j_d = \frac{Sh}{Re\, Sc^{1/3}}$$

where $Sc = \frac{\nu}{D}$ is the Schmidt number and is considered to be constant.
At a temperature of 20 ^{0}C, average temperature of the gas leaving the bed during the experiments, the kinematic viscosity ν of nitrogen is 1.52E-5 m^2/s, and the diffusion coefficient D is 6.36E-6 m^2/s, which gives a Schmidt number equal to 2.39. The Sherwood number can be expressed as a function of the Reynolds number using the experimental

charts. Therefore, the j_d factor can be written as a function of the Reynolds number only: $j_d = ARe^b$.

Table 6. -16+30 Master Beads; K=4, bed depth=24 mm.

-16+30 MASTER BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	18.7	18.3	1.3170	2.974E-02	1.952E-04	0.627	2.535E-02
2	18.8	18.3	1.3170	2.915E-02	1.849E-04	0.627	2.402E-02
3	18.9	18.5	1.3170	3.212E-02	2.330E-04	0.626	3.024E-02
4	19.0	18.5	1.3170	3.145E-02	2.186E-04	0.626	2.837E-02
5	19.0	18.6	1.3170	3.279E-02	2.422E-04	0.625	3.141E-02
6	19.0	18.7	3.1876	3.515E-02	7.222E-04	1.513	9.361E-02
7	19.0	18.7	3.1876	3.499E-02	7.106E-04	1.513	9.211E-02
8	19.2	18.7	3.1876	3.379E-02	6.295E-04	1.513	8.159E-02
9	19.3	18.8	3.1876	3.626E-02	7.885E-04	1.512	1.022E-01
10	19.4	19.0	3.1876	3.392E-02	5.886E-04	1.510	7.617E-02
11	19.4	19.1	5.0582	3.882E-02	1.504E-03	2.394	1.945E-01
12	19.5	19.2	5.0582	3.505E-02	9.850E-04	2.393	1.273E-01
13	19.5	19.3	5.0582	3.852E-02	1.354E-03	2.391	1.750E-01
14	19.6	19.2	5.0582	3.704E-02	1.198E-03	2.393	1.549E-01
15	19.7	19.3	5.0582	3.692E-02	1.148E-03	2.391	1.483E-01
16	19.5	19.2	9.7347	3.822E-02	2.611E-03	4.605	3.375E-01
17	19.5	19.2	9.7347	3.804E-02	2.561E-03	4.605	3.311E-01
18	19.5	19.2	9.7347	3.785E-02	2.510E-03	4.605	3.245E-01
19	19.6	19.2	9.7347	3.789E-02	2.520E-03	4.605	3.258E-01
20	19.6	19.3	9.7347	3.789E-02	2.440E-03	4.602	3.152E-01
21	19.3	19.3	14.4112	4.041E-02	4.795E-03	6.813	6.196E-01
22	19.3	19.2	14.4112	3.905E-02	4.238E-03	6.817	5.480E-01
23	19.3	19.1	14.4112	4.003E-02	4.962E-03	6.822	6.418E-01
24	19.2	19.1	14.4112	3.972E-02	4.770E-03	6.822	6.170E-01
25	19.3	19.1	14.4112	3.967E-02	4.739E-03	6.822	6.130E-01
26	18.9	18.7	19.0877	3.925E-02	7.026E-03	9.059	9.108E-01
27	19.0	18.8	19.0877	3.883E-02	6.375E-03	9.053	8.259E-01
28	18.9	18.8	19.0877	4.139E-02	9.174E-03	9.053	1.189E+00
29	19.0	18.8	19.0877	3.882E-02	6.367E-03	9.053	8.249E-01
30	19.0	18.8	19.0877	4.009E-02	7.550E-03	9.053	9.781E-01
31	19.0	19.0	24.3516	4.143E-02	1.061E-02	11.535	1.373E+00
32	19.0	19.0	24.3516	4.002E-02	8.723E-03	11.535	1.129E+00
33	19.0	18.9	24.3516	4.234E-02	1.296E-02	11.542	1.678E+00
34	19.0	18.9	24.3516	4.205E-02	1.234E-02	11.542	1.598E+00
35	19.0	18.9	24.3516	4.167E-02	1.161E-02	11.542	1.503E+00
36	18.7	18.6	29.2894	4.112E-02	1.505E-02	13.910	1.952E+00
37	18.6	18.7	29.2894	4.292E-02	1.982E-02	13.901	2.569E+00
38	18.7	18.6	29.2894	4.122E-02	1.533E-02	13.910	1.988E+00
39	18.7	18.7	29.2894	4.232E-02	1.761E-02	13.901	2.283E+00
40	18.9	18.7	29.2894	4.218E-02	1.714E-02	13.901	2.222E+00
41	18.8	18.7	34.2273	4.274E-02	2.233E-02	16.244	2.894E+00
42	18.8	18.6	34.2273	4.249E-02	2.281E-02	16.255	2.959E+00
43	18.7	18.6	34.2273	4.279E-02	2.432E-02	16.255	3.153E+00
44	18.7	18.6	34.2273	4.366E-02	2.986E-02	16.255	3.873E+00
45	18.8	18.6	34.2273	4.237E-02	2.224E-02	16.255	2.885E+00

Table 7. -16 + 30 Master Beads; K = 2, bed depth = 24 mm.

-16+30 MASTER BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	19.0	18.7	1.3170	3.112E-02	2.023E-04	0.625	2.602E-02
2	19.0	18.7	1.3170	3.061E-02	1.932E-04	0.625	2.484E-02
3	19.0	18.7	1.3170	3.023E-02	1.869E-04	0.625	2.403E-02
4	19.0	18.7	1.3170	3.029E-02	1.878E-04	0.625	2.415E-02
5	19.1	18.7	1.3170	3.232E-02	2.258E-04	0.625	2.903E-02
6	19.1	18.8	3.1876	3.592E-02	7.602E-04	1.512	9.770E-02
7	19.0	18.8	3.1876	3.312E-02	5.748E-04	1.512	7.388E-02
8	19.1	18.8	3.1876	3.418E-02	6.368E-04	1.512	8.184E-02
9	19.1	18.9	3.1876	3.528E-02	6.904E-04	1.511	8.869E-02
10	19.2	19.0	3.1876	3.567E-02	6.975E-04	1.510	8.955E-02
11	19.1	18.9	5.0582	3.620E-02	1.205E-03	2.398	1.548E-01
12	19.0	18.8	5.0582	3.603E-02	1.220E-03	2.399	1.568E-01
13	19.0	18.8	5.0582	3.580E-02	1.191E-03	2.399	1.531E-01
14	19.0	18.8	5.0582	3.531E-02	1.132E-03	2.399	1.454E-01
15	19.0	18.8	5.0582	3.576E-02	1.186E-03	2.399	1.524E-01
16	19.1	18.9	9.7347	3.707E-02	2.547E-03	4.614	3.272E-01
17	19.2	18.9	9.7347	3.768E-02	2.727E-03	4.614	3.503E-01
18	19.1	18.8	9.7347	3.630E-02	2.418E-03	4.617	3.108E-01
19	19.1	18.8	9.7347	3.789E-02	2.895E-03	4.617	3.721E-01
20	19.0	18.8	9.7347	3.436E-02	1.978E-03	4.617	2.542E-01
21	19.0	18.8	14.4112	3.940E-02	5.184E-03	6.835	6.663E-01
22	19.0	18.7	14.4112	3.788E-02	4.442E-03	6.840	5.712E-01
23	18.9	18.7	14.4112	3.927E-02	5.318E-03	6.840	6.838E-01
24	18.8	18.7	14.4112	3.813E-02	4.584E-03	6.840	5.894E-01
25	18.8	18.6	14.4112	3.776E-02	4.546E-03	6.844	5.849E-01
26	18.8	18.6	19.0877	3.897E-02	7.059E-03	9.065	9.081E-01
27	18.8	18.6	19.0877	3.840E-02	6.539E-03	9.065	8.412E-01
28	18.8	18.8	19.0877	3.998E-02	7.426E-03	9.053	9.544E-01
29	18.8	18.8	19.0877	4.042E-02	7.913E-03	9.053	1.017E+00
30	18.8	18.8	19.0877	4.040E-02	7.884E-03	9.053	1.013E+00
31	18.8	18.6	24.3516	4.091E-02	1.208E-02	11.565	1.554E+00
32	18.8	18.6	24.3516	3.945E-02	9.637E-03	11.565	1.240E+00
33	18.8	18.6	24.3516	4.054E-02	1.137E-02	11.565	1.462E+00
34	18.8	18.6	24.3516	4.067E-02	1.160E-02	11.565	1.493E+00
35	18.8	18.6	24.3516	4.043E-02	1.118E-02	11.565	1.438E+00
36	18.8	18.6	29.2894	4.109E-02	1.498E-02	13.910	1.927E+00
37	18.7	18.5	29.2894	4.047E-02	1.428E-02	13.919	1.838E+00
38	18.5	18.5	29.2894	4.153E-02	1.723E-02	13.919	2.218E+00
39	18.5	18.3	29.2894	4.005E-02	1.485E-02	13.937	1.914E+00
40	18.5	18.4	29.2894	4.067E-02	1.563E-02	13.928	2.013E+00
41	18.5	18.4	34.2273	4.141E-02	2.104E-02	16.276	2.710E+00
42	18.5	18.3	34.2273	3.927E-02	1.525E-02	16.287	1.965E+00
43	18.3	18.2	34.2273	4.023E-02	1.904E-02	16.298	2.455E+00
44	18.3	18.2	34.2273	3.971E-02	1.732E-02	16.298	2.233E+00
45	18.3	18.2	34.2273	4.106E-02	2.247E-02	16.298	2.897E+00

Table 8. -16+30 Master Beads; K=0, bed depth=24 mm.

-16+30 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	17.7	17.6	1.3170	2.477E-02	1.428E-04	0.630	1.866E-02
2	17.7	17.6	1.3170	2.508E-02	1.470E-04	0.630	1.921E-02
3	17.7	17.6	1.3170	2.733E-02	1.816E-04	0.630	2.373E-02
4	17.7	17.6	1.3170	2.499E-02	1.457E-04	0.630	1.904E-02
5	17.7	17.7	1.3170	2.597E-02	1.564E-04	0.629	2.044E-02
6	17.8	17.8	3.1876	2.784E-02	4.417E-04	1.522	5.767E-02
7	17.8	17.8	3.1876	2.692E-02	4.051E-04	1.522	5.290E-02
8	17.8	17.8	3.1876	2.893E-02	4.905E-04	1.522	6.404E-02
9	18.0	17.9	3.1876	2.790E-02	4.348E-04	1.521	5.674E-02
10	18.0	17.9	3.1876	2.832E-02	4.524E-04	1.521	5.904E-02
11	18.0	18.0	5.0582	2.941E-02	7.782E-04	2.412	1.015E-01
12	18.0	18.0	5.0582	2.790E-02	6.758E-04	2.412	8.814E-02
13	18.0	18.0	5.0582	2.975E-02	8.046E-04	2.412	1.049E-01
14	18.0	18.0	5.0582	2.826E-02	6.985E-04	2.412	9.110E-02
15	18.0	18.1	5.0582	2.924E-02	7.489E-04	2.410	9.764E-02
16	18.1	18.0	9.7347	2.974E-02	1.546E-03	4.641	2.016E-01
17	18.1	18.1	9.7347	3.107E-02	1.718E-03	4.638	2.240E-01
18	18.2	18.1	9.7347	3.034E-02	1.600E-03	4.638	2.086E-01
19	18.2	18.1	9.7347	3.197E-02	1.882E-03	4.638	2.453E-01
20	18.2	18.2	9.7347	3.051E-02	1.588E-03	4.635	2.069E-01
21	18.3	18.2	14.4112	3.174E-02	2.650E-03	6.862	3.453E-01
22	18.2	18.2	14.4112	3.243E-02	2.843E-03	6.862	3.704E-01
23	18.3	18.2	14.4112	3.114E-02	2.499E-03	6.862	3.256E-01
24	18.2	18.2	14.4112	3.130E-02	2.537E-03	6.862	3.306E-01
25	18.3	18.2	14.4112	3.128E-02	2.533E-03	6.862	3.300E-01
26	18.4	18.2	19.0877	3.165E-02	3.481E-03	9.089	4.536E-01
27	18.3	18.2	19.0877	3.278E-02	3.905E-03	9.089	5.088E-01
28	18.3	18.2	19.0877	3.280E-02	3.912E-03	9.089	5.097E-01
29	18.3	18.2	19.0877	3.290E-02	3.954E-03	9.089	5.152E-01
30	18.5	18.3	19.0877	3.288E-02	3.836E-03	9.083	4.995E-01
31	18.9	18.9	24.3515	3.452E-02	4.890E-03	11.542	6.349E-01
32	18.9	18.9	24.3515	3.623E-02	5.816E-03	11.542	7.550E-01
33	18.8	18.7	24.3515	3.543E-02	5.686E-03	11.557	7.390E-01
34	18.8	18.7	24.3515	3.691E-02	6.694E-03	11.557	8.700E-01
35	18.7	18.6	24.3515	3.497E-02	5.582E-03	11.565	7.258E-01
36	18.7	18.6	29.2894	3.719E-02	8.621E-03	13.910	1.121E+00
37	18.5	18.4	29.2894	3.573E-02	7.781E-03	13.928	1.013E+00
38	18.5	18.4	29.2894	3.656E-02	8.588E-03	13.928	1.118E+00
39	18.5	18.3	29.2894	3.598E-02	8.303E-03	13.937	1.081E+00
40	18.3	18.2	34.2273	3.521E-02	9.159E-03	16.298	1.193E+00
41	18.5	18.5	34.2273	3.625E-02	9.340E-03	16.266	1.215E+00
42	18.4	18.2	34.2273	3.683E-02	1.121E-02	16.298	1.461E+00
43	18.3	18.2	34.2273	3.502E-02	8.954E-03	16.298	1.167E+00
44	18.3	18.0	34.2273	3.669E-02	1.194E-02	16.319	1.557E+00
45	18.3	18.1	39.1652	3.697E-02	1.362E-02	18.661	1.775E+00
46	18.0	17.9	39.1652	3.608E-02	1.308E-02	18.686	1.707E+00
47	18.0	17.8	39.1652	3.568E-02	1.290E-02	18.698	1.685E+00
48	17.9	17.6	39.1652	3.534E-02	1.334E-02	18.723	1.744E+00
49	17.7	17.4	39.1652	3.651E-02	1.759E-02	18.747	2.301E+00

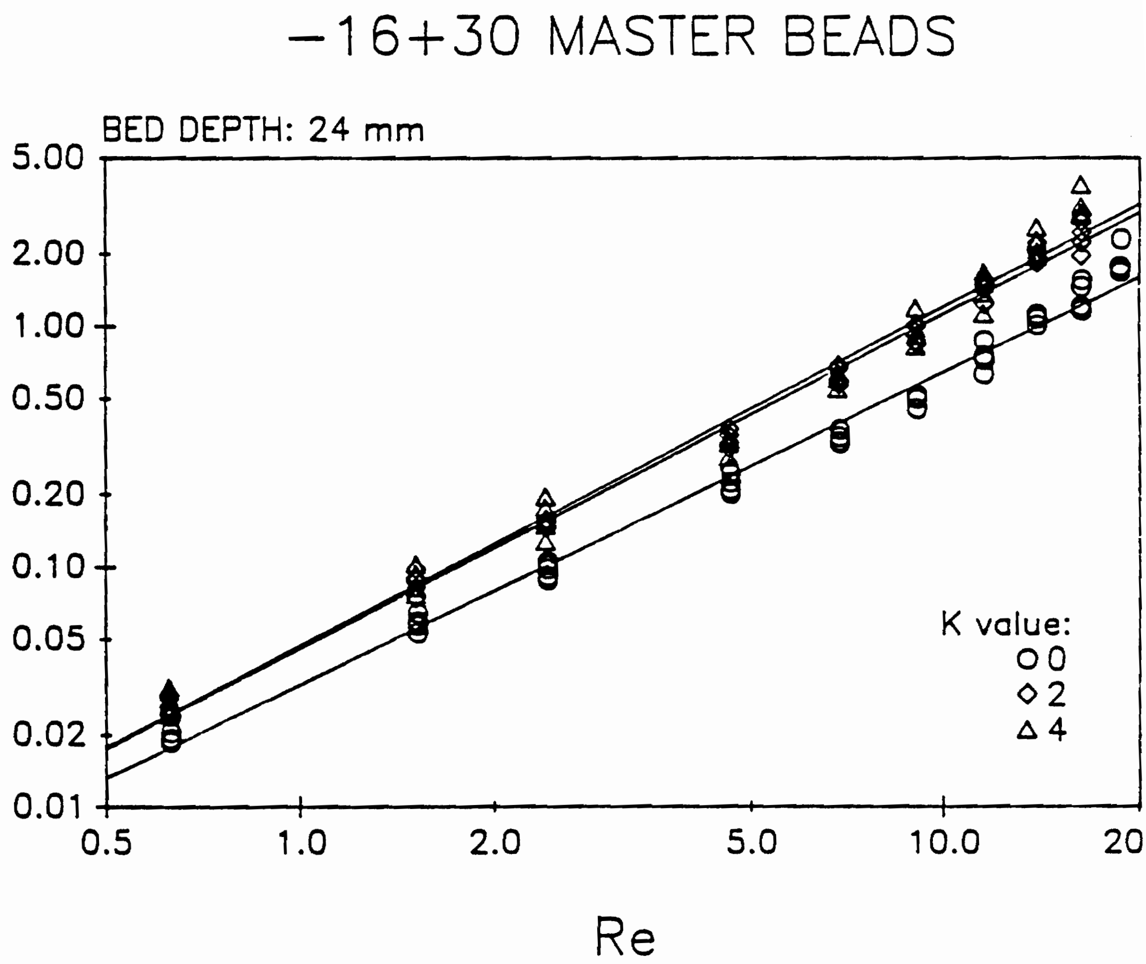


Figure 30. -16+30 Master Beads; bed depth=24 mm.

Table 9. -16 + 30 Master Beads; K = 4, bed depth = 1 mm.

-16+30 MASTER BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	25.0	24.9	1.3170	5.248E-02	2.842E-03	0.601	3.559E-01
2	25.1	25.0	1.3170	5.307E-02	2.860E-03	0.600	3.580E-01
3	25.0	24.9	1.3170	5.299E-02	2.921E-03	0.601	3.658E-01
4	24.9	24.8	1.3170	5.387E-02	3.148E-03	0.601	3.944E-01
5	24.9	24.8	1.3170	5.343E-02	3.072E-03	0.601	3.849E-01
6	24.9	24.8	3.1876	5.466E-02	7.967E-03	1.455	9.982E-01
7	24.9	24.8	3.1876	5.183E-02	6.814E-03	1.455	8.537E-01
8	24.9	24.8	3.1876	5.443E-02	7.863E-03	1.455	9.852E-01
9	24.9	24.8	3.1876	5.396E-02	7.659E-03	1.455	9.596E-01
10	24.9	24.9	3.1876	5.484E-02	7.827E-03	1.454	9.802E-01
11	24.8	24.6	5.0582	5.425E-02	1.306E-02	2.311	1.637E+00
12	24.8	24.7	5.0582	5.586E-02	1.395E-02	2.310	1.749E+00
13	24.8	24.6	5.0582	5.499E-02	1.364E-02	2.311	1.711E+00
14	24.8	24.6	5.0582	5.664E-02	1.508E-02	2.311	1.891E+00
15	24.8	24.6	5.0582	5.563E-02	1.417E-02	2.311	1.777E+00
16	24.7	24.5	9.7347	5.355E-02	2.482E-02	4.451	3.114E+00
17	24.7	24.6	9.7347	5.348E-02	2.404E-02	4.448	3.015E+00
18	24.7	24.5	9.7347	5.326E-02	2.440E-02	4.451	3.061E+00
19	24.7	24.6	9.7347	5.432E-02	2.524E-02	4.448	3.165E+00
20	24.6	24.5	9.7347	5.378E-02	2.514E-02	4.451	3.155E+00
21	24.6	24.4	14.4112	5.223E-02	3.495E-02	6.594	4.388E+00
22	24.5	24.2	14.4112	5.081E-02	3.393E-02	6.602	4.264E+00
23	24.5	24.2	14.4112	5.022E-02	3.280E-02	6.602	4.121E+00
24	24.5	24.2	14.4112	5.044E-02	3.322E-02	6.602	4.174E+00
25	24.5	24.2	14.4112	4.998E-02	3.234E-02	6.602	4.065E+00

Table 10. -16+30 Master Beads; K=2, bed depth=1 mm.

-16+30 MASTER BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	23.9	23.6	1.3170	4.297E-02	2.276E-03	0.606	2.868E-01
2	23.8	23.7	1.3170	4.465E-02	2.450E-03	0.605	3.087E-01
3	24.0	23.8	1.3170	4.298E-02	2.182E-03	0.605	2.748E-01
4	23.9	23.8	1.3170	4.445E-02	2.370E-03	0.605	2.985E-01
5	23.9	23.9	1.3170	4.716E-02	2.704E-03	0.604	3.403E-01
6	23.9	23.8	3.1876	4.575E-02	6.178E-03	1.464	7.780E-01
7	24.0	23.8	3.1876	4.604E-02	6.282E-03	1.464	7.911E-01
8	24.0	23.8	3.1876	4.529E-02	6.018E-03	1.464	7.578E-01
9	24.0	23.9	3.1876	4.681E-02	6.414E-03	1.463	8.073E-01
10	24.0	23.8	3.1876	4.610E-02	6.302E-03	1.464	7.936E-01
11	24.0	23.8	5.0582	4.695E-02	1.051E-02	2.323	1.323E+00
12	24.0	23.8	5.0582	4.651E-02	1.024E-02	2.323	1.290E+00
13	24.0	24.0	5.0582	4.809E-02	1.069E-02	2.320	1.345E+00
14	24.1	23.9	5.0582	4.704E-02	1.031E-02	2.322	1.298E+00
15	24.0	23.9	5.0582	4.784E-02	1.080E-02	2.322	1.360E+00
16	24.1	24.0	9.7347	4.733E-02	1.970E-02	4.465	2.479E+00
17	24.2	24.0	9.7347	4.798E-02	2.046E-02	4.465	2.573E+00
18	24.1	24.1	9.7347	4.773E-02	1.969E-02	4.463	2.476E+00
19	24.1	24.1	9.7347	4.850E-02	2.057E-02	4.463	2.586E+00
20	24.1	24.0	9.7347	4.857E-02	2.117E-02	4.465	2.663E+00
21	24.1	24.1	14.4112	4.805E-02	2.968E-02	6.606	3.731E+00
22	24.2	24.0	14.4112	4.772E-02	2.984E-02	6.610	3.754E+00
23	24.2	24.1	14.4112	4.905E-02	3.142E-02	6.606	3.950E+00
24	24.3	24.1	14.4112	4.781E-02	2.928E-02	6.606	3.682E+00
25	24.5	24.4	14.4112	4.882E-02	2.884E-02	6.594	3.620E+00

Table 11. -16 + 30 Master Beads; K = 0, bed depth = 1 mm.

-16+30 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	25.6	25.3	1.3170	3.928E-02	1.364E-03	0.599	1.704E-01
2	25.6	25.3	1.3170	4.002E-02	1.413E-03	0.599	1.766E-01
3	25.6	25.3	1.3170	3.977E-02	1.396E-03	0.599	1.744E-01
4	25.7	25.4	1.3170	3.958E-02	1.360E-03	0.599	1.699E-01
5	25.7	25.5	1.3170	4.030E-02	1.383E-03	0.598	1.726E-01
6	25.6	25.4	3.1876	4.515E-02	4.278E-03	1.449	5.343E-01
7	25.6	25.4	3.1876	4.204E-02	3.696E-03	1.449	4.616E-01
8	25.7	25.4	3.1876	4.142E-02	3.589E-03	1.449	4.483E-01
9	25.7	25.4	3.1876	4.305E-02	3.874E-03	1.449	4.839E-01
10	25.7	25.5	3.1876	4.453E-02	4.075E-03	1.448	5.088E-01
11	25.7	25.5	5.0582	4.404E-02	6.322E-03	2.298	7.893E-01
12	25.7	25.5	5.0582	4.707E-02	7.282E-03	2.298	9.091E-01
13	25.7	25.5	5.0582	4.648E-02	7.083E-03	2.298	8.843E-01
14	25.7	25.6	5.0582	4.695E-02	7.097E-03	2.297	8.856E-01
15	25.7	25.6	5.0582	4.834E-02	7.573E-03	2.297	9.450E-01
16	25.5	25.3	9.7347	4.564E-02	1.364E-02	4.429	1.704E+00
17	25.5	25.4	9.7347	4.864E-02	1.541E-02	4.426	1.925E+00
18	25.6	25.4	9.7347	4.830E-02	1.517E-02	4.426	1.895E+00
19	25.6	25.4	9.7347	4.633E-02	1.381E-02	4.426	1.725E+00
20	25.6	25.5	9.7347	4.791E-02	1.458E-02	4.423	1.821E+00
21	25.6	25.4	14.4112	4.665E-02	2.076E-02	6.552	2.593E+00
22	25.5	25.3	14.4112	4.623E-02	2.075E-02	6.557	2.594E+00
23	25.5	25.3	14.4112	4.608E-02	2.061E-02	6.557	2.576E+00
24	25.5	25.3	14.4112	4.733E-02	2.188E-02	6.557	2.735E+00
25	25.4	25.2	14.4112	4.639E-02	2.135E-02	6.561	2.669E+00
26	25.2	25.2	19.0877	4.746E-02	2.978E-02	8.690	3.723E+00
27	25.2	25.1	19.0877	4.531E-02	2.738E-02	8.695	3.425E+00
28	25.2	25.0	19.0877	4.544E-02	2.811E-02	8.701	3.519E+00
29	25.1	25.0	19.0877	4.127E-02	2.293E-02	8.701	2.870E+00
30	25.1	24.9	19.0877	4.084E-02	2.286E-02	8.706	2.863E+00

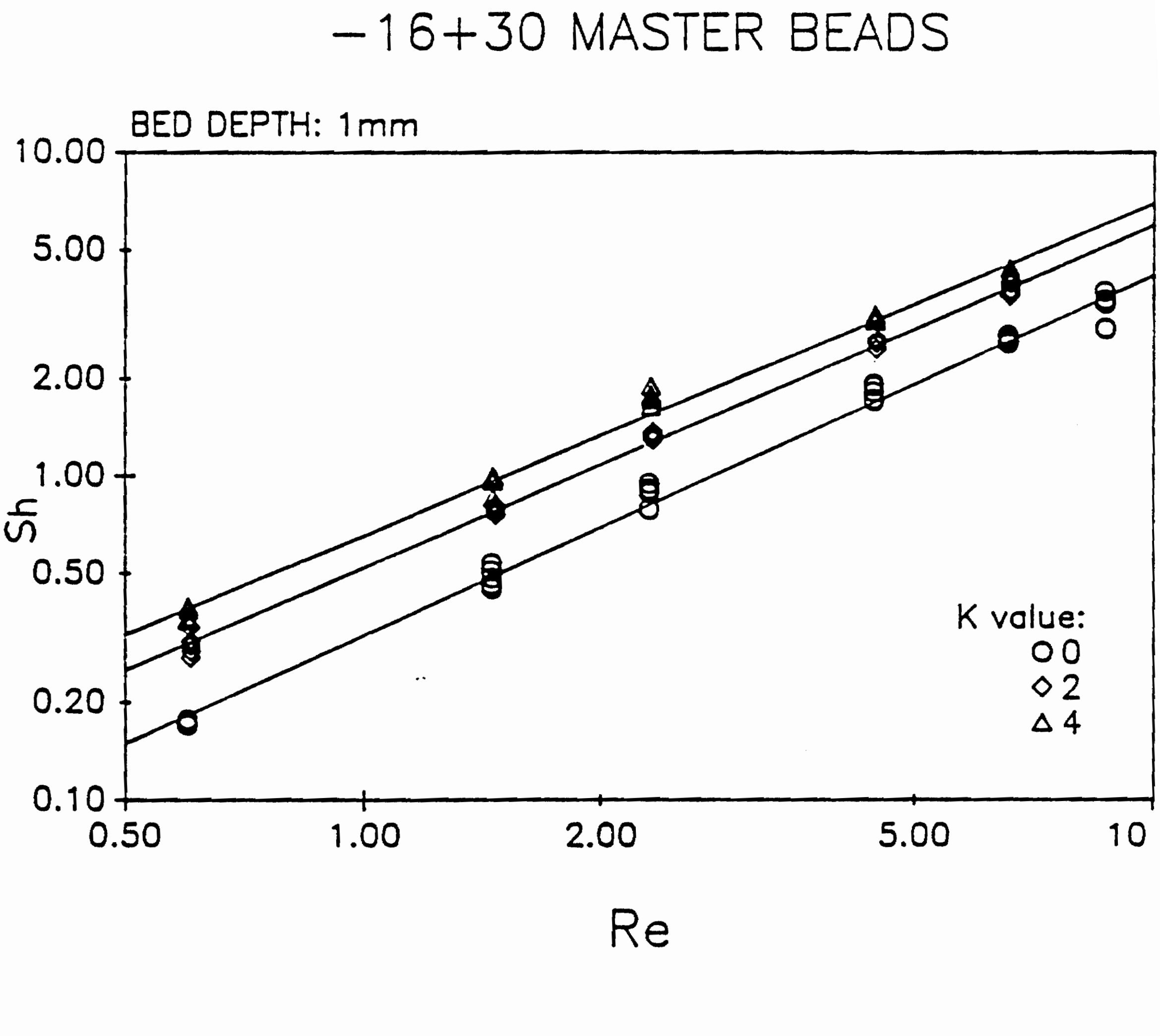


Figure 31. -16 + 30 Master Beads; bed depth = 1 mm.

Table 12. -16 + 30 Low density glass beads; K = 4, depth = 24 mm.

-16+30 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)=24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	15.1	14.7	1.3170	1.988E-02	1.673E-04	0.642	2.199E-02
2	15.4	14.9	1.3170	2.017E-02	1.659E-04	0.641	2.178E-02
3	15.4	14.9	1.3170	2.124E-02	1.882E-04	0.641	2.471E-02
4	15.4	15.0	1.3170	2.233E-02	2.097E-04	0.641	2.751E-02
5	15.4	14.9	1.3170	2.104E-02	1.837E-04	0.641	2.412E-02
6	15.3	15.0	5.0582	2.501E-02	1.136E-03	2.460	1.491E-01
7	15.2	14.9	5.0582	2.478E-02	1.136E-03	2.462	1.492E-01
8	15.2	14.8	5.0582	2.447E-02	1.122E-03	2.463	1.473E-01
9	15.2	15.0	5.0582	2.561E-02	1.235E-03	2.460	1.621E-01
10	15.2	15.0	5.0582	2.552E-02	1.220E-03	2.460	1.601E-01
11	15.0	14.8	9.7347	2.440E-02	2.139E-03	4.741	2.810E-01
12	15.0	14.8	9.7347	2.589E-02	2.654E-03	4.741	3.486E-01
13	15.0	14.8	9.7347	2.610E-02	2.739E-03	4.741	3.598E-01
14	15.0	14.8	9.7347	2.505E-02	2.343E-03	4.741	3.078E-01
15	15.0	14.9	9.7347	2.651E-02	2.814E-03	4.738	3.695E-01
16	16.2	16.2	14.4112	3.052E-02	4.675E-03	6.953	6.096E-01
17	16.5	16.3	14.4112	2.991E-02	4.131E-03	6.949	5.384E-01
18	16.6	16.6	14.4112	3.015E-02	3.852E-03	6.935	5.013E-01
19	16.7	16.7	14.4112	3.147E-02	4.437E-03	6.930	5.771E-01
20	17.1	17.0	14.4112	3.178E-02	4.157E-03	6.917	5.399E-01
21	17.4	17.3	19.0877	3.302E-02	5.823E-03	9.143	7.551E-01
22	17.5	17.4	19.0877	3.298E-02	5.594E-03	9.137	7.249E-01
23	17.5	17.5	19.0877	3.498E-02	7.036E-03	9.131	9.113E-01
24	17.7	17.5	19.0877	3.318E-02	5.543E-03	9.131	7.180E-01
25	17.8	17.6	19.0877	3.300E-02	5.241E-03	9.125	6.785E-01
26	18.1	17.9	24.3515	3.510E-02	7.813E-03	11.618	1.010E+00
27	18.3	18.0	24.3515	3.517E-02	7.601E-03	11.611	9.821E-01
28	18.3	18.0	24.3515	3.599E-02	8.443E-03	11.611	1.091E+00
29	18.4	18.1	24.3515	3.618E-02	8.329E-03	11.603	1.075E+00
30	18.4	18.2	24.3515	3.586E-02	7.707E-03	11.595	9.947E-01
31	19.5	19.2	29.2894	4.089E-02	1.179E-02	13.856	1.513E+00
32	19.5	19.3	29.2894	4.090E-02	1.132E-02	13.847	1.452E+00
33	19.6	19.4	29.2894	4.045E-02	1.029E-02	13.838	1.319E+00
34	19.7	19.4	29.2894	3.960E-02	9.319E-03	13.838	1.195E+00
35	19.7	19.4	29.2894	4.054E-02	1.039E-02	13.838	1.332E+00

Table 13. -16 + 30 Low density glass beads; K = 2, bed depth = 24 mm.

-16+30 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	19.9	19.4	1.3170	2.961E-02	1.679E-04	0.622	2.162E-02
2	19.9	19.4	1.3170	3.006E-02	1.740E-04	0.622	2.240E-02
3	19.9	19.5	1.3170	3.035E-02	1.746E-04	0.622	2.247E-02
4	20.0	19.5	1.3170	3.112E-02	1.859E-04	0.622	2.392E-02
5	20.0	19.5	1.3170	3.074E-02	1.802E-04	0.622	2.319E-02
6	20.0	19.7	5.0582	3.247E-02	7.634E-04	2.385	9.813E-02
7	20.0	19.7	5.0582	3.145E-02	7.039E-04	2.385	9.048E-02
8	20.0	19.7	5.0582	3.239E-02	7.589E-04	2.385	9.755E-02
9	20.0	19.8	5.0582	3.337E-02	8.040E-04	2.383	1.033E-01
10	20.1	19.8	5.0582	3.292E-02	7.748E-04	2.383	9.954E-02
11	20.2	19.9	9.7347	3.352E-02	1.532E-03	4.584	1.967E-01
12	20.3	20.0	9.7347	3.577E-02	1.800E-03	4.581	2.310E-01
13	20.3	20.0	9.7347	3.451E-02	1.623E-03	4.581	2.083E-01
14	20.3	20.0	9.7347	3.397E-02	1.553E-03	4.581	1.994E-01
15	20.4	20.1	9.7347	3.570E-02	1.747E-03	4.578	2.240E-01
16	20.4	20.2	14.4112	3.686E-02	2.778E-03	6.773	3.562E-01
17	20.3	20.1	14.4112	3.736E-02	2.975E-03	6.778	3.816E-01
18	20.4	20.2	14.4112	3.872E-02	3.261E-03	6.773	4.181E-01
19	20.4	20.1	14.4112	3.674E-02	2.821E-03	6.778	3.619E-01
20	20.4	20.2	14.4112	3.847E-02	3.189E-03	6.773	4.089E-01
21	20.3	20.1	19.0877	4.047E-02	5.241E-03	8.977	6.723E-01
22	20.3	20.0	19.0877	3.905E-02	4.719E-03	8.983	6.056E-01
23	20.4	20.1	19.0877	3.943E-02	4.745E-03	8.977	6.087E-01
24	20.3	20.1	19.0877	3.962E-02	4.831E-03	8.977	6.198E-01
25	20.4	20.2	19.0877	4.000E-02	4.854E-03	8.971	6.223E-01
26	20.3	20.1	24.3515	4.190E-02	7.729E-03	11.452	9.914E-01
27	20.2	19.9	24.3515	4.015E-02	6.916E-03	11.467	8.881E-01
28	20.1	19.9	24.3515	3.905E-02	6.202E-03	11.467	7.964E-01
29	20.1	19.9	24.3515	4.211E-02	8.529E-03	11.467	1.095E+00
30	20.1	19.9	24.3515	4.000E-02	6.807E-03	11.467	8.741E-01
31	20.2	19.8	29.2894	4.229E-02	1.089E-02	13.802	1.400E+00
32	20.2	19.8	29.2894	4.227E-02	1.088E-02	13.802	1.398E+00
33	20.3	19.8	29.2894	4.213E-02	1.069E-02	13.802	1.374E+00
34	20.2	19.9	29.2894	4.320E-02	1.166E-02	13.793	1.498E+00
35	20.3	20.0	29.2894	4.257E-02	1.039E-02	13.784	1.334E+00
36	20.8	20.4	34.2273	4.633E-02	1.608E-02	16.066	2.059E+00
37	20.8	20.4	34.2273	4.485E-02	1.339E-02	16.066	1.716E+00
38	20.8	20.4	34.2273	4.611E-02	1.563E-02	16.066	2.002E+00
39	20.8	20.4	34.2273	4.585E-02	1.512E-02	16.066	1.936E+00
40	20.9	20.4	34.2273	4.549E-02	1.447E-02	16.066	1.853E+00
41	20.2	19.9	39.1652	4.554E-02	2.143E-02	18.443	2.751E+00
42	20.1	19.6	39.1652	4.440E-02	2.130E-02	18.479	2.739E+00
43	19.9	19.4	39.1652	4.363E-02	2.111E-02	18.503	2.718E+00
44	19.7	19.2	39.1652	4.290E-02	2.104E-02	18.527	2.711E+00
45	19.5	19.2	39.1652	4.315E-02	2.191E-02	18.527	2.823E+00

Table 14. -16 + 30 Low density glass beads; K = 0, bed depth = 24 mm.

VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	20.7	20.4	1.3170	2.997E-02	1.434E-04	0.618	1.839E-02
2	20.7	20.5	1.3170	3.059E-02	1.473E-04	0.618	1.888E-02
3	20.8	20.6	1.3170	3.159E-02	1.555E-04	0.617	1.992E-02
4	20.8	20.6	1.3170	3.324E-02	1.752E-04	0.617	2.245E-02
5	20.8	20.6	1.3170	3.225E-02	1.630E-04	0.617	2.089E-02
6	21.0	20.8	5.0582	3.733E-02	8.748E-04	2.368	1.120E-01
7	20.9	20.8	5.0582	3.798E-02	9.205E-04	2.368	1.178E-01
8	21.0	20.9	5.0582	3.838E-02	9.264E-04	2.367	1.185E-01
9	21.0	20.9	5.0582	3.858E-02	9.409E-04	2.367	1.204E-01
10	21.1	20.9	5.0582	3.697E-02	8.322E-04	2.367	1.065E-01
11	21.1	21.0	9.7347	4.199E-02	2.326E-03	4.552	2.974E-01
12	21.3	21.1	9.7347	3.945E-02	1.844E-03	4.549	2.356E-01
13	21.4	21.1	9.7347	3.923E-02	1.812E-03	4.549	2.315E-01
14	21.5	21.2	9.7347	4.183E-02	2.168E-03	4.546	2.769E-01
15	21.4	21.3	9.7347	4.119E-02	2.003E-03	4.543	2.558E-01
16	21.3	21.2	14.4112	4.175E-02	3.188E-03	6.730	4.072E-01
17	21.3	21.1	14.4112	4.037E-02	2.932E-03	6.734	3.748E-01
18	21.3	21.2	14.4112	4.263E-02	3.427E-03	6.730	4.377E-01
19	21.3	21.2	14.4112	4.323E-02	3.606E-03	6.730	4.606E-01
20	21.3	21.1	14.4112	4.202E-02	3.353E-03	6.734	4.285E-01
21	21.3	21.3	19.0877	4.502E-02	5.412E-03	8.908	6.910E-01
22	21.3	21.2	19.0877	4.402E-02	5.118E-03	8.913	6.537E-01
23	21.2	21.1	19.0877	4.378E-02	5.170E-03	8.919	6.608E-01
24	21.2	21.1	19.0877	4.336E-02	4.983E-03	8.919	6.368E-01
25	21.1	21.0	19.0877	4.403E-02	5.470E-03	8.925	6.994E-01
26	22.2	22.0	24.3515	4.756E-02	6.811E-03	11.313	8.665E-01
27	22.1	22.0	24.3515	4.824E-02	7.217E-03	11.313	9.182E-01
28	22.1	22.0	24.3515	4.824E-02	7.219E-03	11.313	9.184E-01
29	22.1	22.0	24.3515	4.792E-02	7.023E-03	11.313	8.935E-01
30	22.1	22.0	24.3515	4.665E-02	6.313E-03	11.313	8.031E-01
31	22.2	22.0	29.2894	4.920E-02	9.456E-03	13.607	1.203E+00
32	22.1	22.0	29.2894	4.940E-02	9.631E-03	13.607	1.225E+00
33	22.1	22.0	29.2894	4.883E-02	9.145E-03	13.607	1.163E+00
34	22.1	22.0	29.2894	4.974E-02	9.947E-03	13.607	1.265E+00
35	22.0	22.0	29.2894	4.878E-02	9.104E-03	13.607	1.158E+00
36	22.1	22.1	34.2273	5.194E-02	1.383E-02	15.891	1.759E+00
37	22.0	22.0	34.2273	4.986E-02	1.175E-02	15.901	1.495E+00
38	22.0	21.9	34.2273	4.869E-02	1.096E-02	15.911	1.395E+00
39	22.0	21.9	34.2273	4.925E-02	1.154E-02	15.911	1.469E+00
40	22.1	22.0	34.2273	4.835E-02	1.024E-02	15.901	1.303E+00
41	22.0	21.9	39.1652	5.118E-02	1.600E-02	18.207	2.036E+00
42	22.0	21.9	39.1652	4.904E-02	1.295E-02	18.207	1.648E+00
43	21.5	21.5	39.1652	4.817E-02	1.392E-02	18.254	1.776E+00
44	21.8	21.7	39.1652	4.888E-02	1.379E-02	18.230	1.757E+00
45	21.6	21.6	39.1652	4.888E-02	1.436E-02	18.242	1.831E+00

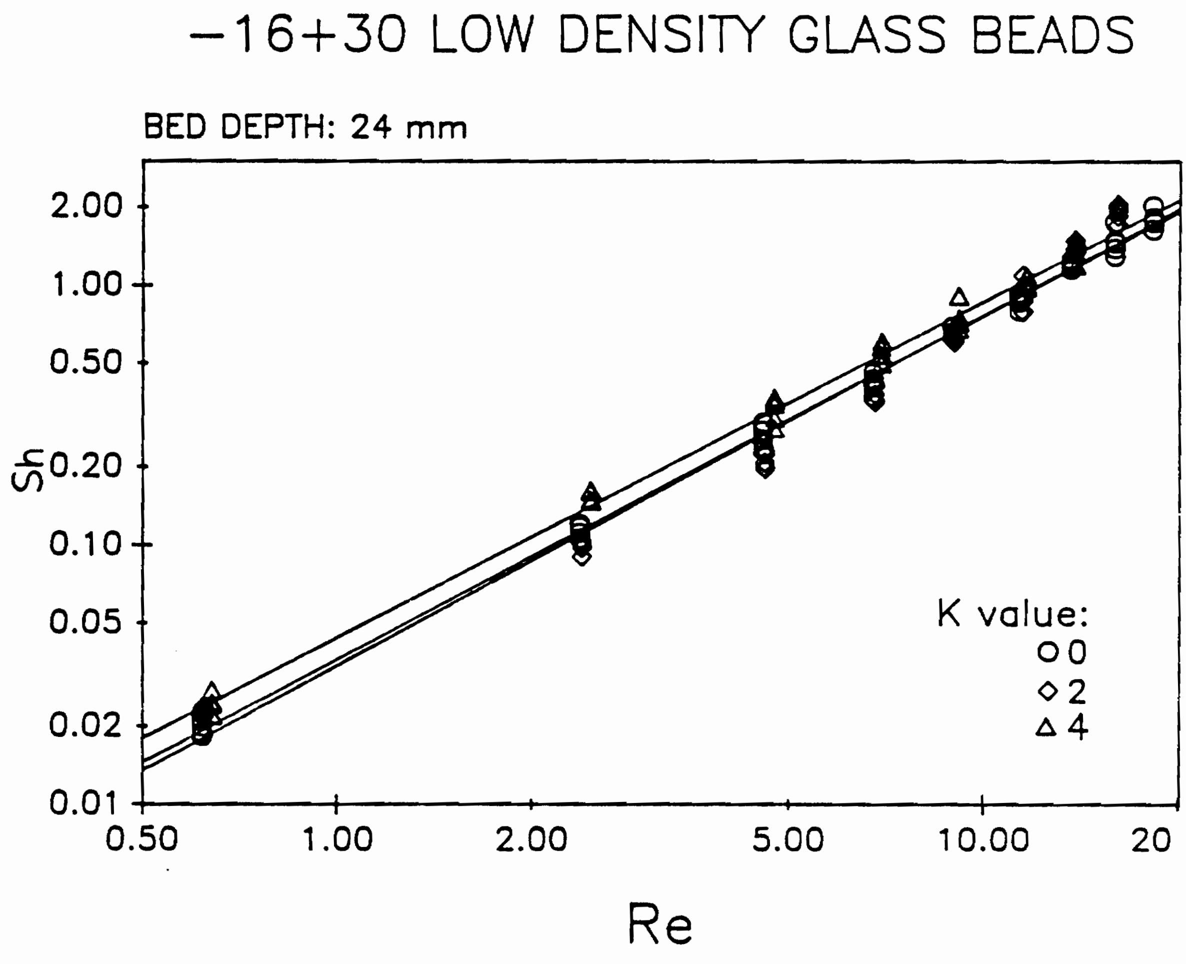


Figure 32. -16 + 30 Low density glass beads; bed depth = 24 mm.

Table 15. -16 + 30 Low density glass beads; K = 4, depth = 1 mm.

-16+30 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH = 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	RE	SH
1	26.6	26.4	1.3170	5.658E-02	2.404E-03	0.595	2.999E-01
2	26.5	26.4	1.3170	5.719E-02	2.470E-03	0.595	3.082E-01
3	26.2	26.3	1.3170	5.447E-02	2.239E-03	0.595	2.795E-01
4	26.3	26.3	1.3170	5.613E-02	2.412E-03	0.595	3.012E-01
5	26.2	26.2	1.3170	5.435E-02	2.278E-03	0.596	2.846E-01
6	26.2	26.0	3.1876	5.750E-02	6.701E-03	1.444	8.377E-01
7	26.0	26.0	3.1876	5.883E-02	7.150E-03	1.444	8.939E-01
8	26.0	25.9	3.1876	5.743E-02	6.854E-03	1.445	8.574E-01
9	25.9	25.8	3.1876	5.517E-02	6.300E-03	1.446	7.884E-01
10	25.8	25.7	3.1876	5.670E-02	6.964E-03	1.447	8.720E-01
11	25.7	25.7	5.0582	5.812E-02	1.188E-02	2.296	1.487E+00
12	25.6	25.5	5.0582	5.640E-02	1.147E-02	2.298	1.438E+00
13	25.6	25.3	5.0582	5.640E-02	1.211E-02	2.301	1.519E+00
14	25.2	25.1	5.0582	5.679E-02	1.308E-02	2.304	1.643E+00
15	25.0	24.9	5.0582	5.575E-02	1.307E-02	2.307	1.643E+00
16	24.9	24.6	9.7347	5.332E-02	2.381E-02	4.448	2.997E+00
17	24.9	24.6	9.7347	5.246E-02	2.267E-02	4.448	2.854E+00
18	24.9	24.6	9.7347	5.500E-02	2.625E-02	4.448	3.306E+00
19	25.0	24.6	9.7347	5.454E-02	2.555E-02	4.448	3.217E+00
20	24.9	24.6	9.7347	5.400E-02	2.476E-02	4.448	3.117E+00
21	25.0	24.6	14.4112	5.429E-02	3.728E-02	6.585	4.694E+00
22	24.9	24.7	14.4112	5.445E-02	3.657E-02	6.581	4.602E+00
23	24.9	24.6	14.4112	5.328E-02	3.516E-02	6.585	4.427E+00
24	24.9	24.6	14.4112	5.006E-02	2.939E-02	6.585	3.701E+00
25	24.9	24.6	14.4112	5.293E-02	3.447E-02	6.585	4.339E+00
26	25.2	24.7	19.0877	5.481E-02	4.947E-02	8.717	6.226E+00
27	25.2	24.8	19.0877	5.362E-02	4.498E-02	8.712	5.658E+00
28	25.2	24.8	19.0877	5.400E-02	4.595E-02	8.712	5.780E+00
29	25.2	24.9	19.0877	5.337E-02	4.321E-02	8.706	5.432E+00
30	25.2	24.9	19.0877	5.268E-02	4.162E-02	8.706	5.233E+00
31	25.6	25.0	24.3515	4.888E-02	4.255E-02	11.100	5.347E+00
32	25.6	25.2	24.3515	4.907E-02	4.109E-02	11.086	5.157E+00
33	25.6	25.3	24.3515	4.938E-02	4.081E-02	11.079	5.120E+00
34	25.7	25.3	24.3515	4.714E-02	3.663E-02	11.079	4.596E+00
35	25.8	25.4	24.3515	5.297E-02	4.761E-02	11.072	5.971E+00

Table 16. -16 + 30 Low density glass beads; K = 2, bed depth = 1 mm.

-16+30 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (1/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	26.4	25.8	1.3170	5.006E-02	2.046E-03	0.597	2.551E-01
2	26.4	25.9	1.3170	5.218E-02	2.208E-03	0.597	2.751E-01
3	26.3	25.9	1.3170	5.319E-02	2.314E-03	0.597	2.883E-01
4	26.2	25.8	1.3170	5.536E-02	2.627E-03	0.597	3.275E-01
5	26.1	25.8	1.3170	5.601E-02	2.710E-03	0.597	3.379E-01
6	25.9	25.5	3.1876	5.552E-02	6.914E-03	1.448	8.633E-01
7	25.8	25.5	3.1876	5.420E-02	6.466E-03	1.448	8.074E-01
8	25.8	25.4	3.1876	5.354E-02	6.412E-03	1.449	8.010E-01
9	25.8	25.4	3.1876	5.310E-02	6.275E-03	1.449	7.839E-01
10	25.6	25.3	3.1876	5.249E-02	6.234E-03	1.450	7.792E-01
11	25.5	25.2	5.0582	5.472E-02	1.138E-02	2.303	1.423E+00
12	25.4	25.1	5.0582	5.466E-02	1.165E-02	2.304	1.457E+00
13	25.4	25.1	5.0582	5.427E-02	1.140E-02	2.304	1.427E+00
14	25.4	25.0	5.0582	5.404E-02	1.157E-02	2.306	1.448E+00
15	25.4	25.0	5.0582	5.413E-02	1.162E-02	2.306	1.455E+00
16	25.2	24.8	9.7347	5.511E-02	2.495E-02	4.443	3.126E+00
17	25.2	24.7	9.7347	5.206E-02	2.160E-02	4.446	2.709E+00
18	25.2	24.7	9.7347	5.194E-02	2.146E-02	4.446	2.690E+00
19	25.2	24.7	9.7347	5.347E-02	2.337E-02	4.446	2.930E+00
20	25.1	24.6	9.7347	5.152E-02	2.150E-02	4.448	2.697E+00
21	25.1	24.6	14.4112	5.410E-02	3.686E-02	6.585	4.624E+00
22	25.0	24.6	14.4112	5.408E-02	3.682E-02	6.585	4.618E+00
23	25.0	24.6	14.4112	5.379E-02	3.621E-02	6.585	4.542E+00
24	25.0	24.5	14.4112	5.336E-02	3.631E-02	6.590	4.557E+00
25	24.9	24.5	14.4112	5.344E-02	3.648E-02	6.590	4.578E+00
26	24.9	24.5	19.0877	5.436E-02	5.102E-02	8.728	6.402E+00
27	25.0	24.5	19.0877	5.276E-02	4.645E-02	8.728	5.830E+00
28	25.0	24.4	19.0877	5.409E-02	5.167E-02	8.733	6.487E+00
29	24.9	24.4	19.0877	5.269E-02	4.754E-02	8.733	5.969E+00
30	24.8	24.4	19.0877	5.315E-02	4.885E-02	8.733	6.133E+00
31	24.8	24.4	24.3515	5.525E-02	7.080E-02	11.142	8.889E+00
32	24.8	24.3	24.3515	5.100E-02	5.646E-02	11.149	7.092E+00
33	24.9	24.3	24.3515	5.199E-02	5.982E-02	11.149	7.514E+00
34	24.8	24.2	24.3515	5.114E-02	5.845E-02	11.156	7.347E+00
35	24.8	24.4	24.3515	5.156E-02	5.680E-02	11.142	7.132E+00

Table 17. -16 + 30 Low density glass beads; K = 0, bed depth = 1 mm.

-16+30 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	24.6	24.4	1.3170	4.742E-02	2.440E-03	0.603	3.045E-01
2	24.5	24.2	1.3170	4.630E-02	2.403E-03	0.603	3.001E-01
3	24.4	24.0	1.3170	4.546E-02	2.398E-03	0.604	2.998E-01
4	24.3	24.0	1.3170	4.737E-02	2.672E-03	0.604	3.341E-01
5	24.3	23.9	1.3170	4.589E-02	2.513E-03	0.604	3.144E-01
6	24.3	23.9	3.1876	4.837E-02	7.021E-03	1.463	8.783E-01
7	24.3	23.9	3.1876	4.592E-02	6.092E-03	1.463	7.621E-01
8	24.2	23.9	3.1876	4.993E-02	7.707E-03	1.463	9.641E-01
9	24.2	23.8	3.1876	4.506E-02	5.935E-03	1.464	7.429E-01
10	24.2	23.8	3.1876	4.802E-02	7.049E-03	1.464	8.822E-01
11	24.2	23.8	5.0582	4.761E-02	1.092E-02	2.323	1.367E+00
12	24.2	23.8	5.0582	4.918E-02	1.200E-02	2.323	1.501E+00
13	24.2	23.7	5.0582	4.649E-02	1.047E-02	2.325	1.311E+00
14	24.2	23.7	5.0582	4.710E-02	1.086E-02	2.325	1.360E+00
15	24.2	23.7	5.0582	4.758E-02	1.118E-02	2.325	1.399E+00
16	24.2	23.7	9.7347	5.235E-02	2.907E-02	4.474	3.640E+00
17	24.1	23.7	9.7347	4.917E-02	2.370E-02	4.474	2.968E+00
18	24.1	23.6	9.7347	4.895E-02	2.400E-02	4.477	3.007E+00
19	24.1	23.6	9.7347	4.770E-02	2.222E-02	4.477	2.783E+00
20	24.0	23.5	9.7347	4.803E-02	2.325E-02	4.479	2.915E+00
21	24.0	23.4	14.4112	5.051E-02	4.162E-02	6.636	5.220E+00
22	23.9	23.3	14.4112	5.215E-02	4.819E-02	6.640	6.047E+00
23	23.9	23.4	14.4112	4.994E-02	4.004E-02	6.636	5.021E+00
24	23.9	23.4	14.4112	4.960E-02	3.914E-02	6.636	4.909E+00
25	23.9	23.3	14.4112	4.945E-02	3.731E-02	6.640	4.682E+00
26	23.8	23.2	19.0877	5.125E-02	6.173E-02	8.800	7.750E+00
27	23.7	23.2	19.0877	4.953E-02	5.467E-02	8.800	6.863E+00
28	23.7	23.1	19.0877	4.911E-02	5.468E-02	8.806	6.869E+00
29	23.7	23.0	19.0877	4.829E-02	5.320E-02	8.811	6.686E+00
30	23.6	23.1	19.0877	4.825E-02	5.157E-02	8.806	6.478E+00

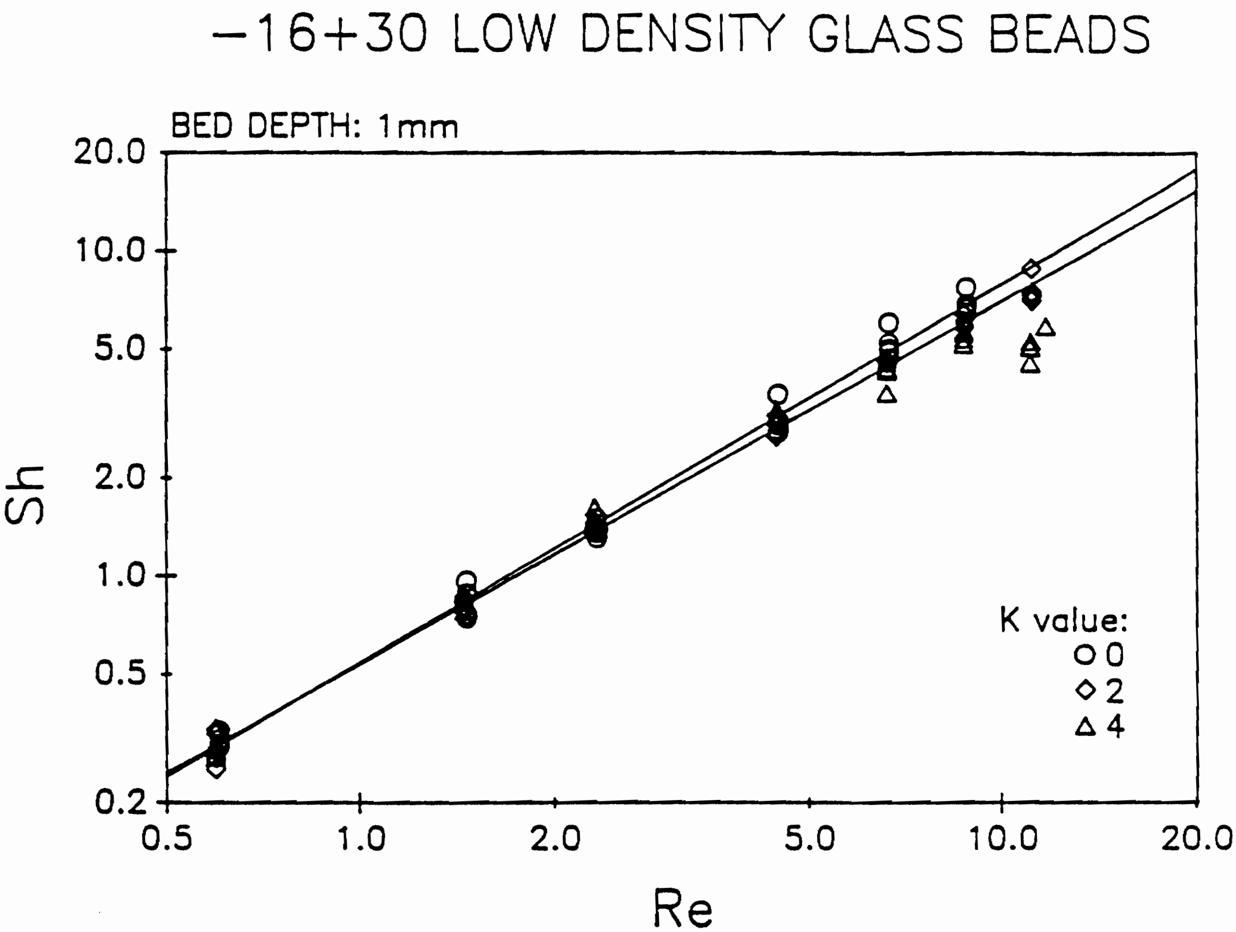


Figure 33. -16+30 Low density glass beads; bed depth = 1 mm.

Table 18. -40 + 50 Master Beads; K = 4, bed depth = 24 mm.

-40+50 MASTER BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	21.6	21.0	1.3170	3.709E-02	6.795E-05	0.258	3.627E-03
2	22.1	21.2	1.3170	3.951E-02	7.772E-05	0.258	4.144E-03
3	22.1	21.3	1.3170	3.846E-02	7.013E-05	0.258	3.738E-03
4	22.2	21.4	1.3170	3.882E-02	7.037E-05	0.258	3.748E-03
5	22.2	21.4	1.3170	3.865E-02	6.951E-05	0.258	3.703E-03
6	22.3	21.5	3.1876	4.369E-02	2.408E-04	0.624	1.282E-02
7	22.3	21.5	3.1876	4.348E-02	2.368E-04	0.624	1.261E-02
8	22.3	21.5	3.1876	4.267E-02	2.219E-04	0.624	1.182E-02
9	22.3	21.6	3.1876	4.328E-02	2.264E-04	0.623	1.205E-02
10	22.3	21.7	3.1876	4.367E-02	2.268E-04	0.623	1.207E-02
11	22.3	21.9	5.0582	4.717E-02	4.501E-04	0.987	2.392E-02
12	22.2	21.9	5.0582	4.666E-02	4.314E-04	0.987	2.292E-02
13	22.2	22.0	5.0582	4.742E-02	4.445E-04	0.986	2.360E-02
14	22.3	22.0	5.0582	4.685E-02	4.239E-04	0.986	2.251E-02
15	22.2	22.0	5.0582	4.671E-02	4.192E-04	0.986	2.226E-02
16	22.0	21.8	9.7347	4.728E-02	9.050E-04	1.901	4.811E-02
17	22.0	21.9	9.7347	4.805E-02	9.352E-04	1.899	4.969E-02
18	22.0	21.8	9.7347	4.745E-02	9.192E-04	1.901	4.886E-02
19	22.0	21.8	9.7347	4.782E-02	9.497E-04	1.901	5.049E-02
20	22.0	21.8	9.7347	4.771E-02	9.406E-04	1.901	5.000E-02
21	21.8	21.7	14.4112	4.690E-02	1.342E-03	2.816	7.136E-02
22	21.8	21.7	14.4112	4.791E-02	1.470E-03	2.816	7.821E-02
23	21.7	21.7	14.4112	4.688E-02	1.339E-03	2.816	7.124E-02
24	21.8	21.7	14.4112	4.958E-02	1.731E-03	2.816	9.208E-02
25	21.7	21.7	14.4112	4.730E-02	1.390E-03	2.816	7.392E-02
26	21.9	21.8	19.0877	5.097E-02	2.540E-03	3.727	1.350E-01
27	21.9	21.9	19.0877	4.970E-02	2.137E-03	3.724	1.135E-01
28	22.1	21.9	19.0877	5.021E-02	2.245E-03	3.724	1.193E-01
29	22.0	21.9	19.0877	4.970E-02	2.137E-03	3.724	1.135E-01
30	22.0	21.9	19.0877	5.034E-02	2.274E-03	3.724	1.208E-01
31	22.1	22.0	24.3516	5.094E-02	2.953E-03	4.749	1.568E-01
32	22.1	22.0	24.3516	5.075E-02	2.900E-03	4.749	1.540E-01
33	22.0	22.0	24.3516	5.126E-02	3.052E-03	4.749	1.621E-01
34	22.1	22.0	24.3516	5.018E-02	2.742E-03	4.749	1.456E-01
35	22.1	22.0	24.3516	5.286E-02	3.630E-03	4.749	1.928E-01
36	22.2	22.0	29.2894	5.134E-02	3.702E-03	5.711	1.966E-01
37	22.2	22.0	29.2894	5.263E-02	4.252E-03	5.711	2.258E-01
38	22.1	21.9	29.2894	5.242E-02	4.363E-03	5.715	2.318E-01
39	22.1	21.9	29.2894	5.117E-02	3.801E-03	5.715	2.020E-01
40	22.1	21.9	29.2894	5.269E-02	4.504E-03	5.715	2.393E-01
41	22.1	22.0	34.2273	5.451E-02	6.247E-03	6.674	3.317E-01
42	22.1	22.0	34.2273	5.257E-02	4.936E-03	6.674	2.621E-01
43	22.1	22.0	34.2273	5.247E-02	4.879E-03	6.674	2.591E-01
44	22.1	22.0	34.2273	5.304E-02	5.208E-03	6.674	2.766E-01
45	22.1	22.0	34.2273	5.244E-02	4.865E-03	6.674	2.584E-01
46	22.1	22.0	39.1652	5.447E-02	7.113E-03	7.637	3.777E-01
47	22.1	21.9	39.1652	5.321E-02	6.412E-03	7.642	3.407E-01
48	22.0	22.0	39.1652	5.262E-02	5.678E-03	7.637	3.015E-01
49	21.9	21.8	39.1652	5.345E-02	6.999E-03	7.647	3.721E-01
50	21.9	21.8	39.1652	5.206E-02	5.890E-03	7.647	3.131E-01

Table 19. -40 + 50 Master Beads; K = 2, bed depth = 24 mm.

-40+50 MASTER BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	22.3	22.2	1.3170	3.869E-02	5.842E-05	0.256	3.110E-03
2	22.3	22.0	1.3170	3.892E-02	6.189E-05	0.257	3.298E-03
3	22.6	22.1	1.3170	3.668E-02	5.239E-05	0.257	2.790E-03
4	22.6	22.1	1.3170	3.861E-02	5.935E-05	0.257	3.161E-03
5	22.7	22.2	1.3170	3.932E-02	6.085E-05	0.256	3.239E-03
6	22.8	22.3	5.0582	4.129E-02	2.602E-04	0.984	1.385E-02
7	22.8	22.4	5.0582	4.397E-02	3.047E-04	0.984	1.620E-02
8	22.9	22.5	5.0582	4.205E-02	2.613E-04	0.983	1.389E-02
9	22.8	22.6	5.0582	4.477E-02	3.055E-04	0.983	1.623E-02
10	22.9	22.6	5.0582	4.355E-02	2.815E-04	0.983	1.496E-02
11	22.8	22.6	9.7347	4.458E-02	5.804E-04	1.891	3.084E-02
12	22.8	22.6	9.7347	4.387E-02	5.536E-04	1.891	2.942E-02
13	22.8	22.7	9.7347	4.632E-02	6.373E-04	1.890	3.384E-02
14	22.8	22.7	9.7347	4.599E-02	6.228E-04	1.890	3.307E-02
15	22.8	22.7	9.7347	4.623E-02	6.332E-04	1.890	3.362E-02
16	22.8	22.7	14.4112	4.801E-02	1.064E-03	2.798	5.651E-02
17	22.9	22.7	14.4112	4.757E-02	1.031E-03	2.798	5.473E-02
18	22.9	22.6	14.4112	4.664E-02	9.920E-04	2.799	5.271E-02
19	22.9	22.6	14.4112	4.724E-02	1.036E-03	2.799	5.504E-02
20	22.8	22.6	14.4112	4.660E-02	9.890E-04	2.799	5.255E-02
21	22.6	22.4	19.0877	4.739E-02	1.473E-03	3.713	7.835E-02
22	22.6	22.4	19.0877	4.646E-02	1.373E-03	3.713	7.305E-02
23	22.5	22.4	19.0877	4.758E-02	1.495E-03	3.713	7.951E-02
24	22.6	22.4	19.0877	4.805E-02	1.550E-03	3.713	8.244E-02
25	22.5	22.4	19.0877	4.785E-02	1.526E-03	3.713	8.115E-02
26	22.5	22.4	24.3515	5.046E-02	2.411E-03	4.736	1.282E-01
27	22.5	22.4	24.3515	5.136E-02	2.610E-03	4.736	1.388E-01
28	22.5	22.3	24.3515	4.814E-02	2.057E-03	4.739	1.095E-01
29	22.5	22.4	24.3515	5.084E-02	2.492E-03	4.736	1.325E-01
30	22.5	22.4	24.3515	5.047E-02	2.413E-03	4.736	1.284E-01
31	22.6	22.4	29.2895	5.181E-02	3.271E-03	5.697	1.740E-01
32	22.6	22.4	29.2895	5.080E-02	2.985E-03	5.697	1.588E-01
33	22.5	22.4	29.2895	4.983E-02	2.748E-03	5.697	1.462E-01
34	22.4	22.3	29.2895	4.954E-02	2.777E-03	5.701	1.478E-01
35	22.4	22.3	29.2895	5.114E-02	3.199E-03	5.701	1.702E-01
36	22.6	22.3	34.2274	5.175E-02	3.960E-03	6.662	2.107E-01
37	22.5	22.3	34.2274	4.980E-02	3.320E-03	6.662	1.767E-01
38	22.5	22.2	34.2274	5.120E-02	3.917E-03	6.666	2.086E-01
39	22.4	22.2	34.2274	5.062E-02	3.710E-03	6.666	1.975E-01
40	22.4	22.2	34.2274	5.098E-02	3.837E-03	6.666	2.043E-01
41	22.5	22.4	39.1652	5.472E-02	5.870E-03	7.618	3.122E-01
42	22.5	22.3	39.1652	5.061E-02	4.078E-03	7.623	2.170E-01
43	22.4	22.3	39.1652	5.190E-02	4.597E-03	7.623	2.446E-01
44	22.5	22.3	39.1652	5.327E-02	5.275E-03	7.623	2.807E-01
45	22.5	22.2	39.1652	5.273E-02	5.223E-03	7.627	2.781E-01

Table 20. -40+50 Master Beads; K=0, bed depth=24 mm.

-40+50 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	24.2	24.2	2.0392	2.565E-02	3.030E-05	0.392	1.592E-03
2	24.4	24.2	2.0392	2.542E-02	2.990E-05	0.392	1.571E-03
3	24.4	24.4	2.0392	2.464E-02	2.781E-05	0.392	1.460E-03
4	24.6	24.5	2.0392	2.556E-02	2.896E-05	0.391	1.520E-03
5	24.6	24.4	2.0392	2.695E-02	3.180E-05	0.392	1.669E-03
6	24.5	24.4	2.0392	2.642E-02	3.085E-05	0.392	1.620E-03
7	24.5	24.4	5.8370	2.668E-02	8.962E-05	1.121	4.705E-03
8	24.5	24.3	5.8370	2.664E-02	9.062E-05	1.122	4.760E-03
9	24.5	24.3	5.8370	2.600E-02	8.737E-05	1.122	4.589E-03
10	24.6	24.3	5.8370	2.603E-02	8.750E-05	1.122	4.596E-03
11	24.6	24.4	5.8370	2.631E-02	8.776E-05	1.121	4.608E-03
12	24.6	24.4	5.8370	2.647E-02	8.854E-05	1.121	4.649E-03
13	23.9	23.8	10.5842	2.896E-02	2.011E-04	2.040	1.059E-02
14	23.9	23.8	10.5842	3.083E-02	2.234E-04	2.040	1.177E-02
15	23.9	23.8	10.5842	3.052E-02	2.196E-04	2.040	1.157E-02
16	24.0	23.8	10.5842	3.174E-02	2.350E-04	2.040	1.237E-02
17	24.0	23.8	10.5842	3.219E-02	2.409E-04	2.040	1.268E-02
18	24.0	23.8	10.5842	3.256E-02	2.458E-04	2.040	1.294E-02
19	24.0	23.8	15.3314	3.352E-02	3.753E-04	2.956	1.977E-02
20	24.0	23.8	15.3314	3.231E-02	3.513E-04	2.956	1.850E-02
21	24.0	23.8	15.3314	3.318E-02	3.683E-04	2.956	1.940E-02
22	24.0	23.8	15.3314	3.106E-02	3.277E-04	2.956	1.726E-02
23	24.0	23.8	15.3314	3.185E-02	3.424E-04	2.956	1.803E-02
24	24.0	23.9	15.3314	3.232E-02	3.460E-04	2.954	1.821E-02
25	24.2	23.9	20.0786	3.724E-02	5.912E-04	3.868	3.112E-02
26	24.1	23.8	20.0786	3.592E-02	5.600E-04	3.871	2.949E-02
27	24.0	23.8	20.0786	3.416E-02	5.090E-04	3.871	2.680E-02
28	24.0	23.7	20.0786	3.214E-02	4.627E-04	3.873	2.438E-02
29	23.8	23.6	20.0786	3.524E-02	5.581E-04	3.876	2.942E-02
30	23.9	23.7	20.0786	3.574E-02	5.641E-04	3.873	2.972E-02
31	24.0	23.8	25.3424	4.279E-02	1.029E-03	4.885	5.416E-02
32	24.4	24.1	25.3424	4.176E-02	9.153E-04	4.876	4.813E-02
33	24.3	24.0	25.3424	3.887E-02	7.994E-04	4.879	4.206E-02
34	24.3	24.0	25.3424	4.298E-02	9.973E-04	4.879	5.247E-02
35	24.1	23.9	25.3424	4.050E-02	8.892E-04	4.882	4.680E-02
36	24.1	23.9	25.3424	4.178E-02	9.533E-04	4.882	5.018E-02
37	24.3	24.0	30.2800	4.613E-02	1.418E-03	5.830	7.459E-02
38	24.3	24.0	30.2800	4.448E-02	1.293E-03	5.830	6.803E-02
39	24.1	23.8	30.2800	4.079E-02	1.100E-03	5.837	5.794E-02
40	24.1	23.8	30.2800	4.442E-02	1.346E-03	5.837	7.089E-02
41	23.9	23.7	30.2800	4.337E-02	1.296E-03	5.841	6.829E-02
42	23.9	23.7	30.2800	4.339E-02	1.298E-03	5.841	6.840E-02
43	23.9	23.6	35.2180	4.363E-02	1.564E-03	6.798	8.243E-02
44	23.9	23.6	35.2180	4.804E-02	2.032E-03	6.798	1.071E-01
45	23.7	23.4	35.2180	4.467E-02	1.738E-03	6.807	9.172E-02
46	22.5	22.2	35.2180	5.258E-02	4.625E-03	6.859	2.455E-01
47	23.7	23.4	35.2180	4.277E-02	1.554E-03	6.807	8.198E-02
48	23.6	23.3	35.2180	4.276E-02	1.587E-03	6.811	8.378E-02
49	23.9	23.6	40.1561	4.868E-02	2.410E-03	7.751	1.270E-01
50	28.2	23.4	40.1561	4.612E-02	2.164E-03	7.761	1.142E-01
51	23.6	23.2	40.1561	4.573E-02	2.219E-03	7.771	1.172E-01
52	23.5	23.2	40.1561	4.670E-02	2.360E-03	7.771	1.247E-01
53	23.5	23.2	40.1561	4.645E-02	2.323E-03	7.771	1.227E-01
54	23.4	23.1	40.1561	4.581E-02	2.288E-03	7.776	1.209E-01

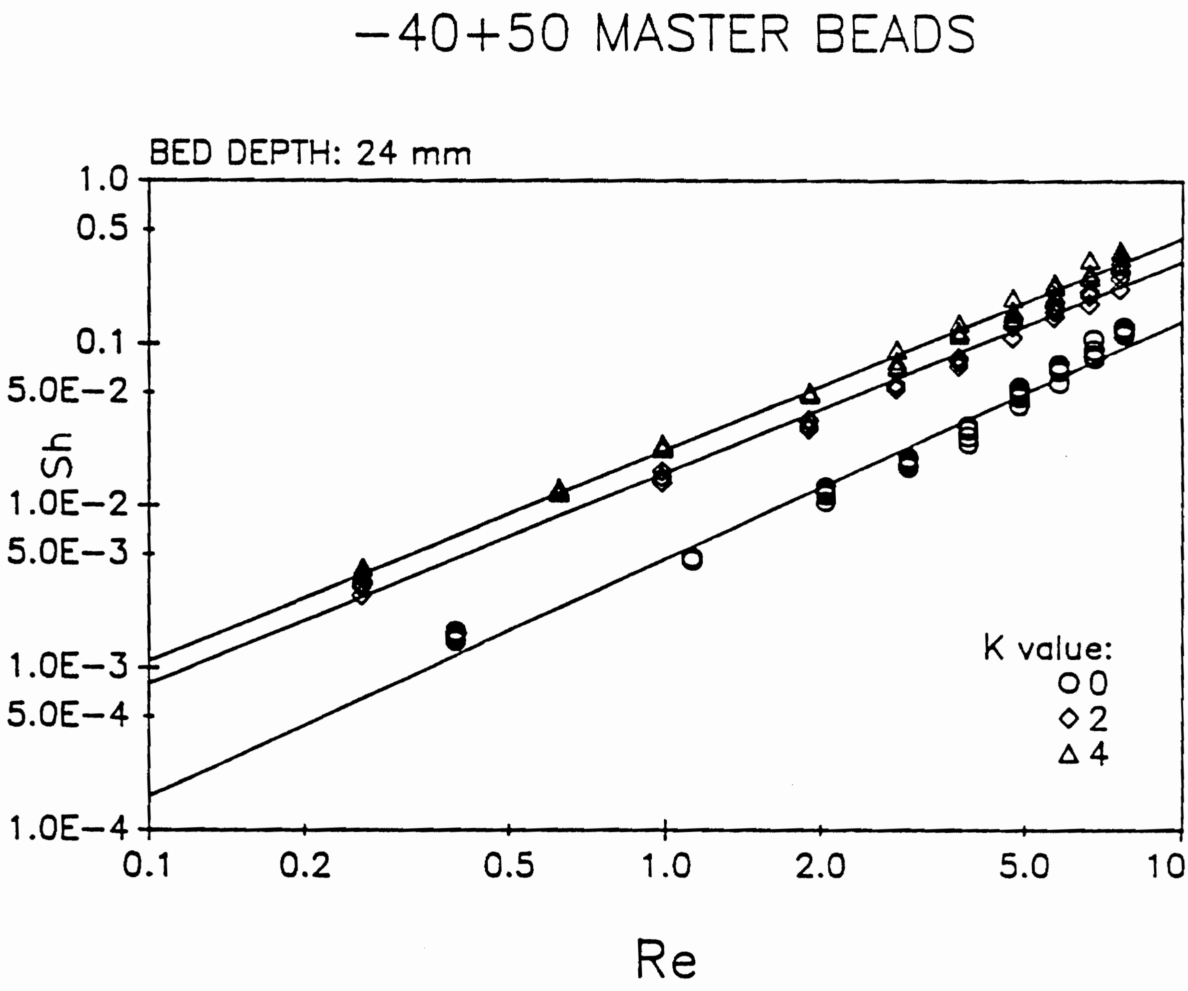


Figure 34. -40 + 50 Master Beads; bed depth = 24 mm.

Table 21. -40+50 Master Beads; K=4, bed depth=1 mm.

-40+50 MASTER BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	23.7	23.6	1.3170	4.515E-02	1.084E-03	0.254	5.732E-02
2	23.7	23.6	1.3170	4.778E-02	1.268E-03	0.254	6.707E-02
3	23.7	23.6	1.3170	4.530E-02	1.093E-03	0.254	5.783E-02
4	23.8	23.8	1.3170	4.835E-02	1.248E-03	0.254	6.595E-02
5	23.8	23.8	1.3170	4.333E-02	9.343E-04	0.254	4.937E-02
6	23.9	23.8	3.1876	4.920E-02	3.178E-03	0.615	1.680E-01
7	24.0	23.8	3.1876	4.762E-02	2.891E-03	0.615	1.528E-01
8	24.1	24.0	3.1876	5.014E-02	3.193E-03	0.614	1.686E-01
9	24.1	24.0	3.1876	4.905E-02	2.993E-03	0.614	1.580E-01
10	24.1	24.1	3.1876	5.265E-02	3.620E-03	0.613	1.910E-01
11	24.3	24.1	5.0582	5.252E-02	5.696E-03	0.973	3.006E-01
12	24.3	24.2	5.0582	5.345E-02	5.864E-03	0.973	3.093E-01
13	24.3	24.2	5.0582	5.349E-02	5.878E-03	0.973	3.100E-01
14	24.3	24.2	5.0582	5.273E-02	5.610E-03	0.973	2.959E-01
15	24.3	24.2	5.0582	5.398E-02	6.062E-03	0.973	3.197E-01
16	24.4	24.4	9.7347	5.473E-02	1.151E-02	1.870	6.066E-01
17	24.3	24.0	9.7347	5.514E-02	1.340E-02	1.874	7.073E-01
18	24.2	24.0	9.7347	5.374E-02	1.221E-02	1.874	6.444E-01
19	24.2	24.1	9.7347	5.498E-02	1.283E-02	1.873	6.771E-01
20	24.3	24.2	9.7347	5.419E-02	1.182E-02	1.872	6.234E-01
21	24.5	24.4	14.4112	5.813E-02	2.122E-02	2.768	1.118E+00
22	24.5	24.4	14.4112	5.678E-02	1.940E-02	2.768	1.022E+00
23	24.6	24.5	14.4112	5.790E-02	2.019E-02	2.766	1.063E+00
24	24.6	24.5	14.4112	5.723E-02	1.933E-02	2.766	1.018E+00
25	24.7	24.5	14.4112	5.820E-02	2.059E-02	2.766	1.084E+00
26	24.7	24.5	19.0877	5.762E-02	2.625E-02	3.663	1.382E+00
27	24.6	24.5	19.0877	5.753E-02	2.610E-02	3.663	1.375E+00
28	24.6	24.5	19.0877	5.670E-02	2.474E-02	3.663	1.303E+00
29	24.5	24.4	19.0877	5.712E-02	2.626E-02	3.666	1.384E+00
30	24.6	24.4	19.0877	5.639E-02	2.505E-02	3.666	1.320E+00

Table 22. -40 + 50 Master Beads; K = 0, bed depth = 1 mm.

-40=50 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	21.8	21.7	1.3170	3.376E-02	7.933E-04	0.257	4.237E-02
2	21.8	21.6	1.3170	2.982E-02	6.243E-04	0.257	3.336E-02
3	21.8	21.7	1.3170	3.263E-02	7.373E-04	0.257	3.938E-02
4	21.8	21.6	1.3170	3.278E-02	7.578E-04	0.257	4.049E-02
5	21.8	21.5	1.3170	3.099E-02	6.854E-04	0.258	3.665E-02
6	21.8	21.7	3.1876	3.728E-02	2.426E-03	0.623	1.296E-01
7	21.8	21.7	3.1876	3.648E-02	2.299E-03	0.623	1.228E-01
8	21.8	21.6	3.1876	3.388E-02	1.971E-03	0.623	1.053E-01
9	21.7	21.6	3.1876	3.710E-02	2.447E-03	0.623	1.308E-01
10	21.7	21.6	3.1876	3.548E-02	2.193E-03	0.623	1.172E-01
11	21.7	21.6	5.0582	3.585E-02	3.568E-03	0.989	1.907E-01
12	21.6	21.5	5.0582	3.804E-02	4.235E-03	0.990	2.264E-01
13	21.7	21.6	5.0582	3.510E-02	3.392E-03	0.989	1.813E-01
14	21.6	21.5	5.0582	3.697E-02	3.931E-03	0.990	2.102E-01
15	21.5	21.5	5.0582	3.671E-02	3.862E-03	0.990	2.065E-01
16	21.5	21.3	9.7347	3.665E-02	7.720E-03	1.907	4.132E-01
17	21.5	21.5	9.7347	3.931E-02	8.924E-03	1.904	4.772E-01
18	21.5	21.4	9.7347	3.827E-02	8.477E-03	1.906	4.535E-01
19	21.5	21.5	9.7347	3.787E-02	8.055E-03	1.904	4.307E-01
20	21.6	21.5	9.7347	3.971E-02	9.185E-03	1.904	4.911E-01
21	21.7	21.6	14.4112	4.112E-02	1.471E-02	2.817	7.863E-01
22	21.6	21.5	14.4112	3.844E-02	1.241E-02	2.819	6.637E-01
23	21.6	21.5	14.4112	4.108E-02	1.505E-02	2.819	8.048E-01
24	21.5	21.3	14.4112	3.727E-02	1.195E-02	2.823	6.394E-01
25	21.5	21.4	14.4112	3.851E-02	1.277E-02	2.821	6.830E-01
26	21.4	21.4	19.0877	4.158E-02	2.126E-02	3.736	1.137E+00
27	21.4	21.3	19.0877	3.802E-02	1.669E-02	3.739	8.934E-01
28	21.5	21.4	19.0877	4.095E-02	2.026E-02	3.736	1.084E+00
29	21.6	21.4	19.0877	3.998E-02	1.883E-02	3.736	1.007E+00
30	21.6	21.5	19.0877	3.918E-02	1.734E-02	3.734	9.269E-01
31	21.7	21.6	24.3515	4.398E-02	3.101E-02	4.761	1.657E+00
32	21.6	21.4	24.3515	4.095E-02	2.584E-02	4.767	1.382E+00
33	21.6	21.5	24.3515	4.206E-02	2.742E-02	4.764	1.466E+00
34	21.6	21.5	24.3515	4.361E-02	3.099E-02	4.764	1.657E+00
35	21.6	21.5	24.3515	4.101E-02	2.530E-02	4.764	1.353E+00
36	21.7	21.5	30.2800	4.124E-02	3.200E-02	5.924	1.711E+00
37	21.7	21.5	30.2800	4.255E-02	3.540E-02	5.924	1.892E+00
38	21.6	21.5	30.2800	4.338E-02	3.781E-02	5.924	2.022E+00
39	21.6	21.4	30.2800	4.354E-02	3.948E-02	5.927	2.112E+00
40	21.7	21.6	30.2800	4.150E-02	3.180E-02	5.920	1.639E+00
41	21.7	21.5	34.2273	4.432E-02	4.618E-02	6.696	2.469E+00
42	21.6	21.4	34.2273	4.444E-02	4.813E-02	6.700	2.575E+00
43	21.3	21.2	34.2273	4.359E-02	4.765E-02	6.709	2.552E+00
44	21.3	21.2	34.2273	4.454E-02	5.181E-02	6.709	2.775E+00
45	21.4	21.2	34.2273	4.384E-02	4.869E-02	6.709	2.607E+00

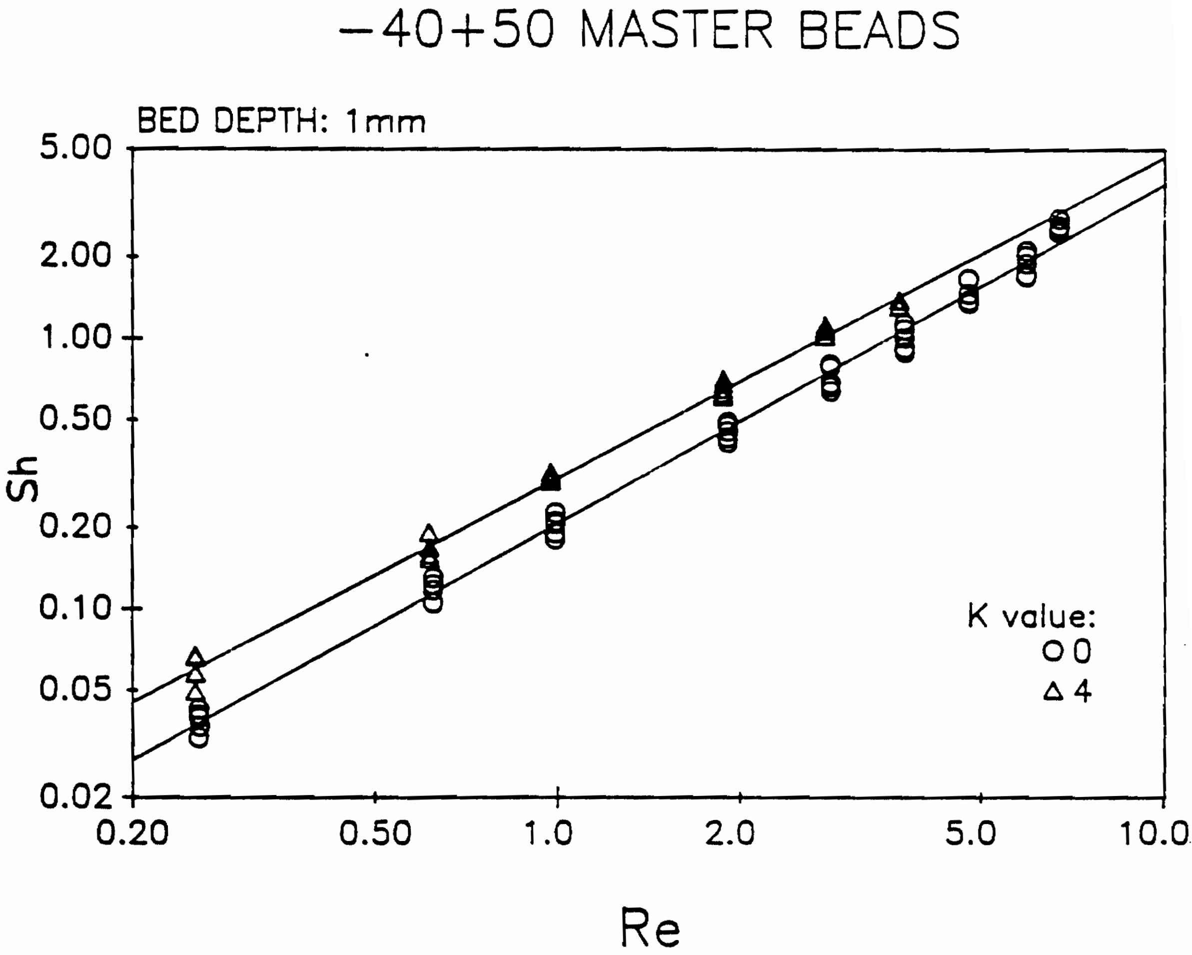


Figure 35. -40 + 50 Master Beads; bed depth = 1 mm.

Table 23. -40 + 50 Master Beads; K = 0, bed depth = 12.7 mm.

-40+50 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 12.7

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	23.3	22.9	1.3170	3.099E-02	5.107E-05	0.255	2.709E-03
2	23.3	22.9	1.3170	2.739E-02	4.116E-05	0.255	2.183E-03
3	23.3	23.0	1.3170	2.529E-02	3.567E-05	0.255	1.891E-03
4	23.3	23.0	1.3170	3.143E-02	5.160E-05	0.255	2.735E-03
5	23.3	23.0	1.3170	2.934E-02	4.561E-05	0.255	2.418E-03
6	23.3	23.2	5.0582	3.531E-02	2.398E-04	0.979	1.270E-02
7	23.3	23.2	5.0582	3.473E-02	2.319E-04	0.979	1.228E-02
8	23.4	23.3	5.0582	3.575E-02	2.417E-04	0.978	1.279E-02
9	23.4	23.3	5.0582	3.505E-02	2.322E-04	0.978	1.229E-02
10	23.4	23.4	5.0582	3.609E-02	2.421E-04	0.978	1.281E-02
11	23.3	23.4	9.7347	3.766E-02	5.086E-04	1.881	2.691E-02
12	23.6	23.6	9.7347	3.811E-02	5.029E-04	1.879	2.658E-02
13	23.6	23.6	9.7347	3.846E-02	5.126E-04	1.879	2.709E-02
14	23.6	23.6	9.7347	3.829E-02	5.078E-04	1.879	2.684E-02
15	23.6	23.6	9.7347	3.928E-02	5.364E-04	1.879	2.835E-02
16	23.7	23.7	14.4112	4.121E-02	8.671E-04	2.780	4.581E-02
17	23.7	23.7	14.4112	4.348E-02	9.848E-04	2.780	5.203E-02
18	23.7	23.8	14.4112	4.377E-02	9.795E-04	2.778	5.172E-02
19	23.7	23.7	14.4112	4.029E-02	8.241E-04	2.780	4.353E-02
20	23.7	23.7	14.4112	4.204E-02	9.082E-04	2.780	4.798E-02
21	23.8	23.8	19.0877	4.441E-02	1.345E-03	3.680	7.104E-02
22	23.8	23.8	19.0877	4.714E-02	1.574E-03	3.680	8.309E-02
23	23.8	23.8	19.0877	4.270E-02	1.222E-03	3.680	6.453E-02
24	23.8	23.8	19.0877	4.486E-02	1.380E-03	3.680	7.287E-02
25	23.8	23.8	19.0877	4.785E-02	1.642E-03	3.680	8.668E-02
26	23.8	24.0	24.3515	4.919E-02	2.155E-03	4.689	1.137E-01
27	23.8	24.0	24.3515	4.627E-02	1.822E-03	4.683	9.613E-02
28	23.8	24.0	24.3515	4.852E-02	2.072E-03	4.689	1.093E-01
29	23.8	24.0	24.3515	4.927E-02	2.165E-03	4.689	1.142E-01
30	23.8	23.9	24.3515	4.836E-02	2.105E-03	4.691	1.111E-01
31	23.9	24.0	29.2895	4.948E-02	2.637E-03	5.639	1.391E-01
32	23.8	24.0	29.2895	4.888E-02	2.546E-03	5.639	1.343E-01
33	23.8	24.0	29.2895	5.134E-02	2.950E-03	5.639	1.556E-01
34	23.8	23.9	29.2895	4.885E-02	2.606E-03	5.643	1.375E-01
35	23.8	23.9	29.2895	4.985E-02	2.767E-03	5.643	1.460E-01
36	23.8	23.9	34.2274	5.057E-02	3.380E-03	6.594	1.784E-01
37	23.8	23.9	34.2274	5.151E-02	3.583E-03	6.594	1.891E-01
38	23.8	24.0	34.2274	5.203E-02	3.597E-03	6.590	1.897E-01
39	23.8	23.9	34.2274	5.099E-02	3.467E-03	6.594	1.830E-01
40	23.7	23.9	34.2274	5.138E-02	3.554E-03	6.594	1.876E-01

Table 24. -60 + 70 Master Beads; K = 4, bed depth = 1 mm.

-60+70 MASTER BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	21.8	21.6	1.3170	3.580E-02	6.008E-04	0.167	2.095E-02
2	21.8	21.6	1.3170	3.665E-02	6.363E-04	0.167	2.218E-02
3	21.9	21.7	1.3170	3.788E-02	6.774E-04	0.167	2.360E-02
4	21.9	21.8	1.3170	3.839E-02	6.862E-04	0.167	2.390E-02
5	22.0	21.8	1.3170	3.651E-02	6.049E-04	0.167	2.107E-02
6	22.0	21.9	3.1876	4.040E-02	1.864E-03	0.403	6.489E-02
7	22.1	22.0	3.1876	4.236E-02	2.089E-03	0.403	7.267E-02
8	22.1	22.0	3.1876	4.142E-02	1.955E-03	0.403	6.801E-02
9	22.2	22.1	3.1876	4.184E-02	1.964E-03	0.403	6.828E-02
10	22.2	22.1	3.1876	4.172E-02	1.948E-03	0.403	6.773E-02
11	22.2	22.1	5.0582	4.349E-02	3.501E-03	0.639	1.217E-01
12	22.2	22.0	5.0582	4.297E-02	3.461E-03	0.640	1.204E-01
13	22.1	22.0	5.0582	4.247E-02	3.339E-03	0.640	1.162E-01
14	22.1	22.0	5.0582	4.257E-02	3.365E-03	0.640	1.171E-01
15	22.0	21.9	5.0582	4.395E-02	3.824E-03	0.640	1.331E-01
16	22.0	21.9	9.7347	4.488E-02	7.905E-03	1.232	2.752E-01
17	22.0	22.0	9.7347	4.519E-02	7.868E-03	1.231	2.737E-01
18	22.1	22.0	9.7347	4.653E-02	8.744E-03	1.231	3.042E-01
19	22.1	22.0	9.7347	4.456E-02	7.498E-03	1.231	2.608E-01
20	22.1	22.1	9.7347	4.647E-02	8.434E-03	1.231	2.933E-01
21	22.1	22.0	14.4112	4.749E-02	1.402E-02	1.823	4.876E-01
22	22.1	22.0	14.4112	4.581E-02	1.222E-02	1.823	4.253E-01
23	22.1	22.1	14.4112	4.800E-02	1.415E-02	1.822	4.919E-01
24	22.2	22.1	14.4112	4.735E-02	1.341E-02	1.822	4.662E-01
25	22.2	22.1	14.4112	4.726E-02	1.331E-02	1.822	4.628E-01
26	22.2	22.1	19.0877	4.892E-02	2.028E-02	2.413	7.052E-01
27	22.2	22.1	19.0877	4.807E-02	1.884E-02	2.413	6.552E-01
28	22.3	22.1	19.0877	4.877E-02	2.001E-02	2.413	6.957E-01
29	22.3	22.1	19.0877	4.821E-02	1.907E-02	2.413	6.632E-01
30	22.3	22.2	19.0877	4.898E-02	1.967E-02	2.412	6.837E-01

Table 25. -60+70 Master Beads; K=2, bed depth=1 mm.

-60+70 MASTER BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	22.3	22.2	1.3170	3.341E-02	4.601E-04	0.166	1.602E-02
2	22.4	22.1	1.3170	3.278E-02	4.503E-04	0.166	1.569E-02
3	22.4	22.2	1.3170	3.241E-02	4.326E-04	0.166	1.506E-02
4	22.3	22.2	1.3170	3.507E-02	5.105E-04	0.166	1.777E-02
5	22.4	22.2	1.3170	3.392E-02	4.750E-04	0.166	1.654E-02
6	22.6	22.4	3.1876	3.894E-02	1.515E-03	0.402	5.270E-02
7	22.7	22.4	3.1876	3.627E-02	1.283E-03	0.402	4.462E-02
8	22.8	22.5	3.1876	3.609E-02	1.245E-03	0.402	4.329E-02
9	22.8	22.6	3.1876	3.749E-02	1.330E-03	0.402	4.623E-02
10	22.8	22.7	3.1876	3.908E-02	1.437E-03	0.401	4.992E-02
11	22.8	22.8	5.0582	4.292E-02	2.834E-03	0.637	9.836E-02
12	22.8	22.8	5.0582	4.177E-02	2.636E-03	0.637	9.152E-02
13	22.8	22.7	5.0582	4.114E-02	2.591E-03	0.637	8.997E-02
14	22.8	22.8	5.0582	4.280E-02	2.813E-03	0.637	9.766E-02
15	22.8	22.8	5.0582	4.298E-02	2.844E-03	0.637	9.873E-02
16	23.1	22.9	9.7347	4.270E-02	5.255E-03	1.224	1.823E-01
17	23.1	23.0	9.7347	4.621E-02	6.422E-03	1.224	2.227E-01
18	23.2	23.0	9.7347	4.479E-02	5.857E-03	1.224	2.031E-01
19	23.2	23.1	9.7347	4.498E-02	5.786E-03	1.223	2.005E-01
20	23.2	23.1	9.7347	4.523E-02	5.878E-03	1.223	2.037E-01
21	23.1	22.9	14.4112	4.597E-02	9.607E-03	1.813	3.333E-01
22	23.1	23.0	14.4112	4.586E-02	9.293E-03	1.811	3.223E-01
23	23.2	23.1	14.4112	4.692E-02	9.701E-03	1.810	3.362E-01
24	23.3	23.1	14.4112	4.777E-02	1.026E-02	1.810	3.557E-01
25	23.3	23.2	14.4112	4.658E-02	9.248E-03	1.809	3.204E-01
26	23.3	23.2	19.0877	4.808E-02	1.351E-02	2.396	4.679E-01
27	23.3	23.3	19.0877	5.006E-02	1.499E-02	2.395	5.192E-01
28	23.3	23.2	19.0877	4.838E-02	1.378E-02	2.396	4.773E-01
29	23.3	23.2	19.0877	4.937E-02	1.473E-02	2.396	5.103E-01
30	23.3	23.2	19.0877	4.742E-02	1.293E-02	2.396	4.478E-01
31	23.3	23.2	24.3515	5.033E-02	2.008E-02	3.057	6.958E-01
32	23.1	23.0	24.3515	4.866E-02	1.897E-02	3.061	6.577E-01
33	23.1	23.0	24.3515	4.977E-02	2.052E-02	3.061	7.116E-01
34	23.0	23.0	24.3515	4.891E-02	1.929E-02	3.061	6.691E-01
35	23.1	23.0	24.3515	4.813E-02	1.828E-02	3.061	6.339E-01

Table 26. -60+70 Master Beads; K=0, bed depth=1 mm.

-60+70 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	23.2	23.1	1.3170	3.635E-02	4.679E-04	0.165	1.622E-02
2	23.1	23.0	1.3170	3.364E-02	4.071E-04	0.166	1.412E-02
3	23.2	23.0	1.3170	3.325E-02	3.980E-04	0.166	1.380E-02
4	23.1	23.0	1.3170	3.585E-02	4.627E-04	0.166	1.604E-02
5	23.2	23.0	1.3170	3.333E-02	3.997E-04	0.166	1.386E-02
6	23.1	23.0	3.1876	3.950E-02	1.387E-03	0.401	4.809E-02
7	23.1	23.0	3.1876	3.610E-02	1.136E-03	0.401	3.941E-02
8	23.1	23.0	3.1876	3.752E-02	1.234E-03	0.401	4.280E-02
9	23.1	23.0	3.1876	3.929E-02	1.370E-03	0.401	4.752E-02
10	23.0	22.9	3.1876	3.741E-02	1.250E-03	0.401	4.337E-02
11	22.9	22.9	5.0582	3.907E-02	2.189E-03	0.636	7.594E-02
12	22.9	22.9	5.0582	3.910E-02	2.192E-03	0.636	7.607E-02
13	23.0	22.8	5.0582	3.928E-02	2.263E-03	0.637	7.854E-02
14	23.0	22.8	5.0582	3.807E-02	2.103E-03	0.637	7.299E-02
15	23.0	22.9	5.0582	4.073E-02	2.420E-03	0.636	8.395E-02
16	23.1	22.9	9.7347	4.353E-02	5.538E-03	1.224	1.921E-01
17	23.2	22.9	9.7347	4.027E-02	4.529E-03	1.224	1.571E-01
18	23.2	23.0	9.7347	4.130E-02	4.892E-03	1.224	1.696E-01
19	23.3	23.1	9.7347	4.114E-02	4.574E-03	1.223	1.585E-01
20	23.5	23.3	9.7347	4.370E-02	5.104E-03	1.221	1.767E-01
21	23.6	23.4	14.4112	4.296E-02	7.072E-03	1.807	2.448E-01
22	23.8	23.6	14.4112	4.404E-02	7.208E-03	1.805	2.492E-01
23	23.8	23.6	14.4112	4.743E-02	8.809E-03	1.805	3.046E-01
24	23.7	23.6	14.4112	4.385E-02	7.127E-03	1.805	2.464E-01
25	23.7	23.6	14.4112	4.588E-02	8.024E-03	1.805	2.774E-01
26	23.7	23.6	19.0877	4.630E-02	1.090E-02	2.390	3.768E-01
27	23.7	23.6	19.0877	4.381E-02	9.422E-03	2.390	3.257E-01
28	23.8	23.6	19.0877	4.640E-02	1.096E-02	2.390	3.790E-01
29	23.9	23.7	19.0877	4.939E-02	1.282E-02	2.389	4.431E-01
30	23.9	23.7	19.0877	4.853E-02	1.216E-02	2.389	4.202E-01
31	24.0	23.9	24.3515	5.108E-02	1.721E-02	3.043	5.940E-01
32	24.3	24.1	24.3515	4.950E-02	1.484E-02	3.040	5.118E-01
33	24.3	24.1	24.3515	5.144E-02	1.665E-02	3.040	5.741E-01
34	24.3	24.1	24.3515	5.010E-02	1.537E-02	3.040	5.301E-01
35	24.3	24.1	24.3515	4.971E-02	1.502E-02	3.040	5.180E-01
36	24.2	24.2	29.2894	5.550E-02	2.509E-02	3.654	8.650E-01
37	24.1	24.0	29.2894	5.057E-02	1.952E-02	3.658	6.735E-01
38	24.1	24.0	29.2894	5.161E-02	2.080E-02	3.658	7.177E-01
39	24.0	23.9	29.2894	5.069E-02	2.020E-02	3.661	6.973E-01
40	24.2	24.0	34.2273	5.213E-02	2.511E-02	4.275	8.663E-01
41	24.1	23.9	34.2273	5.125E-02	2.444E-02	4.278	8.438E-01
42	24.1	23.8	34.2273	5.292E-02	2.804E-02	4.280	9.686E-01
43	24.1	23.8	34.2273	5.271E-02	2.766E-02	4.280	9.554E-01
44	24.0	23.7	34.2273	5.270E-02	2.851E-02	4.283	9.851E-01

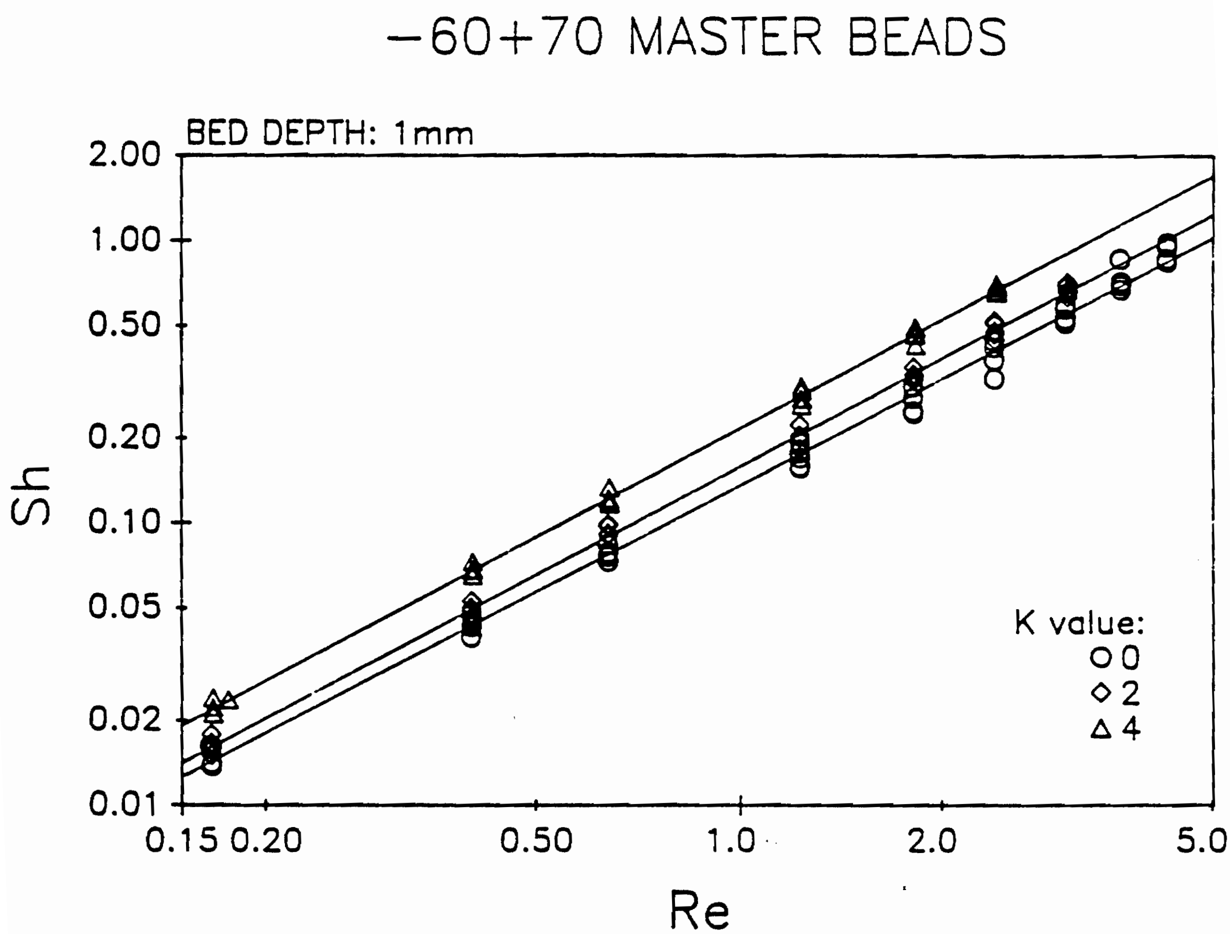


Figure 36. -60 + 70 Master Beads; bed depth = 1 mm.

Table 27. -60 + 70 Low density glass beads; K = 4, depth = 24 mm.

-60+70 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	24.5	24.3	1.3170	5.046E-02	5.227E-05	0.164	1.779E-03
2	24.7	24.4	1.3170	4.966E-02	4.873E-05	0.164	1.657E-03
3	24.7	24.3	1.3170	4.955E-02	4.964E-05	0.164	1.689E-03
4	24.6	24.2	1.3170	5.216E-02	5.932E-05	0.164	2.020E-03
5	24.6	24.2	1.3170	5.247E-02	6.044E-05	0.164	2.058E-03
6	24.3	24.0	5.0582	5.273E-02	2.499E-04	0.632	8.517E-03
7	24.3	24.1	5.0582	5.486E-02	2.783E-04	0.631	9.479E-03
8	24.3	24.0	5.0582	5.550E-02	3.002E-04	0.632	1.023E-02
9	24.4	24.0	5.0582	5.498E-02	2.897E-04	0.632	9.872E-03
10	24.4	24.1	5.0582	5.571E-02	2.945E-04	0.631	1.003E-02
11	24.3	24.0	9.7347	5.824E-02	7.045E-04	1.216	2.401E-02
12	24.2	24.0	9.7347	5.763E-02	6.727E-04	1.216	2.293E-02
13	24.1	24.0	9.7347	5.647E-02	6.182E-04	1.216	2.107E-02
14	24.2	23.9	9.7347	5.735E-02	6.840E-04	1.217	2.332E-02
15	24.1	23.9	9.7347	5.911E-02	7.856E-04	1.217	2.679E-02
16	23.9	23.8	14.4112	5.756E-02	1.070E-03	1.802	3.652E-02
17	23.7	23.6	14.4112	5.868E-02	1.280E-03	1.805	4.370E-02
18	23.6	23.4	14.4112	5.571E-02	1.080E-03	1.807	3.693E-02
19	23.6	23.4	14.4112	5.866E-02	1.403E-03	1.807	4.797E-02
20	23.6	23.5	14.4112	5.806E-02	1.267E-03	1.806	4.328E-02
21	23.4	23.3	19.0877	5.695E-02	1.660E-03	2.395	5.677E-02
22	23.4	23.3	19.0877	5.813E-02	1.853E-03	2.395	6.338E-02
23	23.3	23.2	19.0877	5.561E-02	1.539E-03	2.396	5.266E-02
24	23.3	23.3	19.0877	5.756E-02	1.756E-03	2.395	6.004E-02
25	23.3	23.2	19.0877	5.739E-02	1.811E-03	2.396	6.196E-02
26	23.3	23.2	24.3515	5.854E-02	2.592E-03	3.057	8.869E-02
27	23.5	23.2	24.3515	5.773E-02	2.389E-03	3.057	8.175E-02
28	23.3	23.1	24.3515	5.872E-02	2.787E-03	3.059	9.541E-02
29	23.2	23.1	24.3515	5.851E-02	2.726E-03	3.059	9.332E-02
30	23.2	23.1	24.3515	5.950E-02	3.043E-03	3.059	1.042E-01
31	23.3	23.2	29.2894	6.137E-02	4.328E-03	3.677	1.481E-01
32	23.3	23.1	29.2894	6.049E-02	4.133E-03	3.679	1.415E-01
33	23.1	23.0	29.2894	5.984E-02	4.065E-03	3.682	1.392E-01
34	23.2	23.0	29.2894	5.953E-02	3.910E-03	3.682	1.339E-01
35	23.1	23.0	29.2894	5.950E-02	3.894E-03	3.682	1.334E-01
36	23.2	23.1	34.2273	6.225E-02	6.174E-03	4.300	2.114E-01
37	23.2	23.1	34.2273	6.184E-02	5.807E-03	4.300	1.988E-01
38	23.1	23.0	34.2273	6.141E-02	5.897E-03	4.302	2.020E-01
39	23.1	23.0	34.2273	6.171E-02	6.172E-03	4.302	2.114E-01
40	23.1	22.9	34.2273	5.905E-02	4.582E-03	4.305	1.570E-01

Table 28. -60 + 70 Low density glass beads; K = 2, bed depth = 24 mm.

-60+70 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	20.4	20.2	1.3170	3.415E-02	4.628E-05	0.169	1.625E-03
2	20.5	20.3	1.3170	3.407E-02	4.501E-05	0.168	1.580E-03
3	20.5	20.3	1.3170	3.366E-02	4.361E-05	0.168	1.531E-03
4	20.6	20.4	1.3170	3.413E-02	4.426E-05	0.168	1.552E-03
5	20.7	20.4	1.3170	3.279E-02	4.000E-05	0.168	1.403E-03
6	23.0	22.9	5.0582	4.497E-02	2.046E-04	0.636	7.087E-03
7	22.9	22.6	5.0582	4.455E-02	2.148E-04	0.637	7.450E-03
8	22.9	22.6	5.0582	4.479E-02	2.183E-04	0.637	7.571E-03
9	22.8	22.5	5.0582	4.369E-02	2.078E-04	0.638	7.211E-03
10	22.7	22.4	5.0582	4.535E-02	2.395E-04	0.638	8.317E-03
11	22.6	22.4	9.7347	4.866E-02	5.919E-04	1.228	2.055E-02
12	22.6	22.3	9.7347	4.713E-02	5.419E-04	1.229	1.882E-02
13	22.6	22.4	9.7347	4.845E-02	5.819E-04	1.228	2.020E-02
14	22.5	22.4	9.7347	4.718E-02	5.275E-04	1.228	1.831E-02
15	22.5	22.4	9.7347	4.843E-02	5.810E-04	1.228	2.017E-02
16	22.4	22.3	14.4112	5.027E-02	1.039E-03	1.820	3.609E-02
17	22.4	22.3	14.4112	4.949E-02	9.708E-04	1.820	3.372E-02
18	22.3	22.2	14.4112	4.850E-02	9.244E-04	1.821	3.213E-02
19	22.4	22.3	14.4112	4.965E-02	9.844E-04	1.820	3.420E-02
20	22.3	22.2	14.4112	4.970E-02	1.025E-03	1.821	3.564E-02
21	22.3	22.2	19.0877	5.001E-02	1.396E-03	2.412	4.853E-02
22	22.3	22.2	19.0877	4.912E-02	1.291E-03	2.412	4.486E-02
23	22.3	22.2	19.0877	5.012E-02	1.409E-03	2.412	4.898E-02
24	22.3	22.2	19.0877	5.007E-02	1.403E-03	2.412	4.876E-02
25	22.3	22.3	19.0877	4.975E-02	1.314E-03	2.410	4.566E-02
26	22.3	22.3	24.3515	5.122E-02	1.912E-03	3.075	6.641E-02
27	22.3	22.3	24.3515	5.188E-02	2.035E-03	3.075	7.071E-02
28	22.3	22.3	24.3515	5.135E-02	1.935E-03	3.075	6.723E-02
29	22.3	22.3	24.3515	5.105E-02	1.882E-03	3.075	6.537E-02
30	22.3	22.3	24.3515	5.174E-02	2.008E-03	3.075	6.976E-02
31	22.5	22.3	29.2894	5.341E-02	2.854E-03	3.698	9.916E-02
32	22.5	22.4	29.2894	5.163E-02	2.295E-03	3.696	7.967E-02
33	22.4	22.4	29.2894	5.296E-02	2.605E-03	3.696	9.046E-02
34	22.4	22.4	29.2894	5.225E-02	2.431E-03	3.696	8.441E-02
35	22.4	22.4	29.2894	5.281E-02	2.565E-03	3.696	8.907E-02
36	22.4	22.4	34.2273	5.460E-02	3.610E-03	4.319	1.253E-01
37	22.5	22.4	34.2273	5.294E-02	3.036E-03	4.319	1.054E-01
38	22.5	22.5	34.2273	5.425E-02	3.312E-03	4.316	1.149E-01
39	22.5	22.4	34.2273	5.354E-02	3.226E-03	4.319	1.120E-01
40	22.3	22.3	34.2273	5.309E-02	3.227E-03	4.322	1.121E-01

Table 29. -60 + 70 Low density glass beads; K = 0, bed depth = 24 mm.

-60+70 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 24

No	Tbed (C)	Tgas (C)	N2 FLOW (1/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	18.2	17.8	1.3170	2.502E-02	3.488E-05	0.171	1.222E-03
2	18.0	17.6	1.3170	2.460E-02	3.485E-05	0.171	1.222E-03
3	17.9	17.4	1.3170	2.527E-02	3.857E-05	0.172	1.354E-03
4	17.6	17.1	1.3170	2.412E-02	3.662E-05	0.172	1.287E-03
5	17.5	17.0	1.3170	2.345E-02	3.500E-05	0.172	1.231E-03
6	17.0	16.9	5.0582	2.719E-02	2.000E-04	0.661	7.037E-03
7	16.9	16.8	5.0582	2.506E-02	1.641E-04	0.662	5.779E-03
8	16.9	16.8	5.0582	2.633E-02	1.871E-04	0.662	6.586E-03
9	16.9	16.6	5.0582	2.208E-02	1.267E-04	0.663	4.465E-03
10	16.8	16.6	5.0582	2.437E-02	1.596E-04	0.663	5.624E-03
11	16.7	16.4	9.7347	2.580E-02	3.740E-04	1.277	1.320E-02
12	16.7	16.5	9.7347	2.639E-02	3.893E-04	1.276	1.373E-02
13	16.6	16.4	9.7347	2.738E-02	4.467E-04	1.277	1.576E-02
14	16.5	16.4	9.7347	2.469E-02	3.319E-04	1.277	1.171E-02
15	16.5	16.3	9.7347	2.684E-02	4.312E-04	1.278	1.522E-02
16	16.5	16.4	14.4112	2.762E-02	6.805E-04	1.891	2.401E-02
17	16.5	16.3	14.4112	2.734E-02	6.767E-04	1.892	2.389E-02
18	16.5	16.2	14.4112	2.506E-02	5.351E-04	1.893	1.890E-02
19	16.4	16.2	14.4112	2.725E-02	6.884E-04	1.893	2.431E-02
20	16.4	16.2	14.4112	2.791E-02	7.462E-04	1.893	2.636E-02
21	16.4	16.2	19.0877	2.886E-02	1.115E-03	2.508	3.939E-02
22	16.4	16.2	19.0877	2.763E-02	9.549E-04	2.508	3.373E-02
23	16.3	16.2	19.0877	2.954E-02	1.222E-03	2.508	4.315E-02
24	16.3	16.2	19.0877	2.736E-02	9.244E-04	2.508	3.265E-02
25	16.3	16.2	19.0877	2.737E-02	9.255E-04	2.508	3.269E-02
26	16.3	16.1	24.3515	2.927E-02	1.556E-03	3.201	5.498E-02
27	16.3	16.1	24.3515	2.738E-02	1.217E-03	3.201	4.299E-02
28	16.3	16.1	24.3515	2.702E-02	1.163E-03	3.201	4.109E-02
29	16.3	16.1	24.3515	2.988E-02	1.696E-03	3.201	5.992E-02
30	16.4	16.2	24.3515	2.917E-02	1.483E-03	3.199	5.237E-02
31	16.3	16.2	29.2894	3.142E-02	2.474E-03	3.848	8.738E-02
32	16.3	16.2	29.2894	2.889E-02	1.718E-03	3.848	6.066E-02
33	16.3	16.1	29.2894	2.978E-02	2.011E-03	3.851	7.105E-02
34	16.3	16.2	29.2894	3.130E-02	2.426E-03	3.848	8.568E-02
35	16.4	16.2	29.2894	3.129E-02	2.422E-03	3.848	8.554E-02
36	16.3	16.1	34.2273	3.076E-02	2.719E-03	4.500	9.609E-02
37	16.4	16.1	34.2273	3.065E-02	2.671E-03	4.500	9.438E-02
38	16.2	16.1	34.2273	3.058E-02	2.642E-03	4.500	9.334E-02
39	16.2	16.0	34.2273	3.057E-02	2.749E-03	4.503	9.718E-02
40	16.1	16.1	34.2273	3.173E-02	3.181E-03	4.500	1.124E-01
41	15.8	15.8	39.1652	3.260E-02	5.058E-03	5.159	1.790E-01
42	15.8	15.5	39.1652	3.071E-02	4.069E-03	5.170	1.442E-01
43	15.6	15.5	39.1652	3.123E-02	4.511E-03	5.170	1.599E-01
44	15.5	15.3	39.1652	3.001E-02	3.944E-03	5.177	1.400E-01
45	15.4	15.3	39.1652	3.089E-02	4.720E-03	5.177	1.675E-01

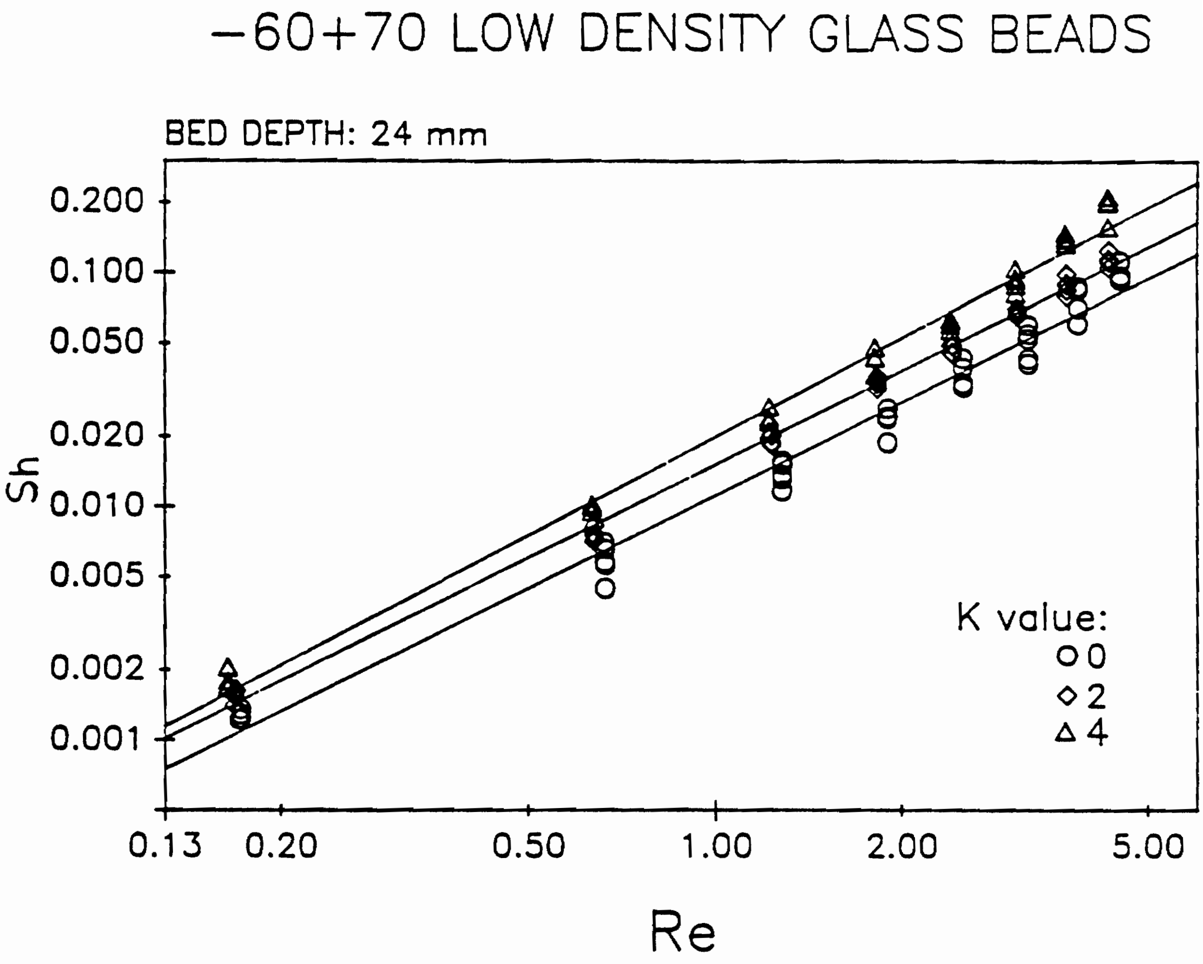


Figure 37. -60 + 70 Low density glass beads; bed depth = 24 mm.

Table 30. -60 + 70 Low density glass beads; K = 4, depth = 1 mm.

-60+70 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	21.0	20.9	3.1876	2.993E-02	1.112E-03	0.406	3.898E-02
2	21.0	20.8	3.1876	2.863E-02	1.033E-03	0.406	3.622E-02
3	22.1	20.9	3.1876	2.862E-02	1.015E-03	0.406	3.559E-02
4	21.0	21.0	3.1876	3.244E-02	1.300E-03	0.406	4.554E-02
5	21.2	21.1	3.1876	3.258E-02	1.288E-03	0.406	4.512E-02
6	21.2	21.2	5.0582	3.647E-02	2.630E-03	0.643	9.207E-02
7	21.2	21.2	5.0582	3.553E-02	2.461E-03	0.643	8.614E-02
8	21.3	21.2	5.0582	3.820E-02	2.981E-03	0.643	1.043E-01
9	21.2	21.1	5.0582	3.574E-02	2.551E-03	0.644	8.933E-02
10	21.3	21.2	5.0582	3.736E-02	2.803E-03	0.643	9.814E-02
11	21.4	21.3	9.7347	3.903E-02	5.957E-03	1.237	2.084E-01
12	21.5	21.3	9.7347	3.602E-02	4.802E-03	1.237	1.680E-01
13	21.5	21.4	9.7347	3.968E-02	6.102E-03	1.236	2.134E-01
14	21.5	21.4	9.7347	3.804E-02	5.416E-03	1.236	1.894E-01
15	21.6	21.5	9.7347	4.050E-02	6.325E-03	1.235	2.211E-01
16	22.3	21.9	14.4112	4.182E-02	9.331E-03	1.824	3.255E-01
17	22.2	21.9	14.4112	4.216E-02	9.564E-03	1.824	3.336E-01
18	22.2	22.0	14.4112	4.175E-02	9.060E-03	1.823	3.159E-01
19	22.2	22.0	14.4112	4.120E-02	8.713E-03	1.823	3.038E-01
20	22.2	22.0	14.4112	4.066E-02	8.397E-03	1.823	2.928E-01
21	22.1	21.9	19.0877	4.045E-02	1.122E-02	2.416	3.914E-01
22	22.0	21.9	19.0877	4.044E-02	1.121E-02	2.416	3.910E-01
23	21.9	21.8	19.0877	4.027E-02	1.135E-02	2.418	3.960E-01
24	21.8	21.6	19.0877	3.974E-02	1.145E-02	2.421	4.001E-01
25	21.8	21.6	19.0877	4.134E-02	1.287E-02	2.421	4.498E-01

Table 31. -60 + 70 Low density glass beads; K = 2, bed depth = 1 mm.

-60+70 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (1/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	22.7	22.2	3.1876	2.930E-02	8.641E-04	0.403	3.005E-02
2	22.9	22.4	3.1876	2.719E-02	7.345E-04	0.402	2.552E-02
3	23.0	22.6	3.1876	3.121E-02	9.124E-04	0.402	3.167E-02
4	22.9	22.5	3.1876	3.293E-02	1.029E-03	0.402	3.573E-02
5	22.9	22.5	3.1876	2.994E-02	8.580E-04	0.402	2.980E-02
6	22.9	22.4	5.0582	3.461E-02	1.841E-03	0.638	6.395E-02
7	23.0	22.5	5.0582	3.149E-02	1.497E-03	0.638	5.198E-02
8	23.0	22.6	5.0582	3.869E-02	2.275E-03	0.637	7.898E-02
9	23.1	22.7	5.0582	3.634E-02	1.936E-03	0.637	6.715E-02
10	23.1	22.6	5.0582	3.448E-02	1.763E-03	0.637	6.119E-02
11	23.1	22.7	9.7347	1.427E-02	8.523E-04	1.226	2.957E-02
12	23.2	22.8	9.7347	4.031E-02	4.643E-03	1.225	1.610E-01
13	23.1	22.8	9.7347	3.832E-02	4.116E-03	1.225	1.427E-01
14	23.2	22.9	9.7347	3.925E-02	4.267E-03	1.224	1.479E-01
15	23.2	22.9	9.7347	4.030E-02	4.544E-03	1.224	1.575E-01
16	23.2	22.9	14.4112	4.050E-02	6.808E-03	1.813	2.359E-01
17	23.2	22.9	14.4112	3.979E-02	6.522E-03	1.813	2.260E-01
18	23.3	23.0	14.4112	4.151E-02	7.086E-03	1.811	2.455E-01
19	23.3	23.0	14.4112	4.012E-02	6.517E-03	1.811	2.258E-01
20	23.3	23.0	14.4112	3.998E-02	6.466E-03	1.811	2.240E-01
21	23.5	23.1	19.0877	3.891E-02	7.881E-03	2.398	2.729E-01
22	23.5	23.2	19.0877	4.134E-02	8.902E-03	2.396	3.081E-01
23	23.5	23.2	19.0877	4.090E-02	8.675E-03	2.396	3.002E-01
24	23.6	23.2	19.0877	4.047E-02	8.461E-03	2.396	2.928E-01
25	23.6	23.2	19.0877	4.356E-02	1.016E-02	2.396	3.517E-01

Table 32. -60 + 70 Low density glass beads; K = 0, bed depth = 1 mm.

-60+70 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	21.5	21.4	1.3170	2.840E-02	3.815E-04	0.167	1.331E-02
2	21.4	21.3	1.3170	2.830E-02	3.849E-04	0.167	1.344E-02
3	21.4	21.3	1.3170	2.806E-02	3.787E-04	0.167	1.322E-02
4	21.4	21.3	1.3170	2.803E-02	3.779E-04	0.167	1.319E-02
5	21.4	21.3	1.3170	2.832E-02	3.854E-04	0.167	1.345E-02
6	21.4	21.3	3.1876	3.001E-02	1.045E-03	0.405	3.648E-02
7	21.3	21.2	3.1876	2.788E-02	9.198E-04	0.405	3.213E-02
8	21.3	21.2	3.1876	2.761E-02	9.034E-04	0.405	3.155E-02
9	21.3	21.2	3.1876	2.984E-02	1.050E-03	0.405	3.667E-02
10	21.4	21.2	3.1876	2.943E-02	1.021E-03	0.405	3.568E-02
11	22.2	22.0	5.0582	3.089E-02	1.564E-03	0.640	5.441E-02
12	22.1	22.0	5.0582	3.015E-02	1.493E-03	0.640	5.193E-02
13	22.2	22.1	5.0582	3.049E-02	1.501E-03	0.639	5.218E-02
14	22.2	22.1	5.0582	3.164E-02	1.612E-03	0.639	5.606E-02
15	22.2	22.1	5.0582	3.226E-02	1.677E-03	0.639	5.829E-02
16	22.2	22.1	9.7347	3.379E-02	3.551E-03	1.231	1.235E-01
17	22.2	22.0	9.7347	3.218E-02	3.265E-03	1.231	1.136E-01
18	22.2	22.1	9.7347	3.500E-02	3.832E-03	1.231	1.332E-01
19	22.2	22.1	9.7347	3.540E-02	3.932E-03	1.231	1.367E-01
20	22.3	22.2	9.7347	3.646E-02	4.126E-03	1.230	1.434E-01
21	22.3	22.1	14.4112	3.738E-02	6.607E-03	1.822	2.297E-01
22	22.4	22.2	14.4112	3.640E-02	6.084E-03	1.821	2.114E-01
23	22.5	22.2	14.4112	3.567E-02	5.810E-03	1.821	2.019E-01
24	22.6	22.4	14.4112	4.267E-02	8.749E-03	1.818	3.037E-01
25	22.7	22.4	14.4112	3.677E-02	5.992E-03	1.818	2.080E-01
26	22.9	22.7	19.0877	3.971E-02	8.962E-03	2.404	3.106E-01
27	22.9	22.7	19.0877	4.167E-02	1.013E-02	2.404	3.510E-01
28	22.9	22.7	19.0877	4.073E-02	9.543E-03	2.404	3.308E-01
29	22.9	22.7	19.0877	3.931E-02	8.744E-03	2.404	3.031E-01
30	22.9	22.6	19.0877	3.992E-02	9.271E-03	2.405	3.215E-01
31	22.9	22.7	24.3515	4.160E-02	1.286E-02	3.067	4.458E-01
32	23.0	22.8	24.3515	4.106E-02	1.216E-02	3.065	4.214E-01
33	23.0	22.8	24.3515	4.142E-02	1.244E-02	3.065	4.308E-01
34	23.1	22.8	24.3515	4.112E-02	1.221E-02	3.065	4.231E-01
35	23.1	22.8	24.3515	4.092E-02	1.206E-02	3.065	4.177E-01
36	23.2	23.0	30.2800	4.277E-02	1.608E-02	3.806	5.567E-01
37	23.2	23.0	30.2800	4.017E-02	1.374E-02	3.806	4.755E-01
38	23.3	23.0	30.2800	4.141E-02	1.480E-02	3.806	5.123E-01
39	23.3	23.0	30.2800	4.396E-02	1.732E-02	3.806	5.995E-01
40	23.3	23.0	30.2800	4.336E-02	1.668E-02	3.806	5.773E-01

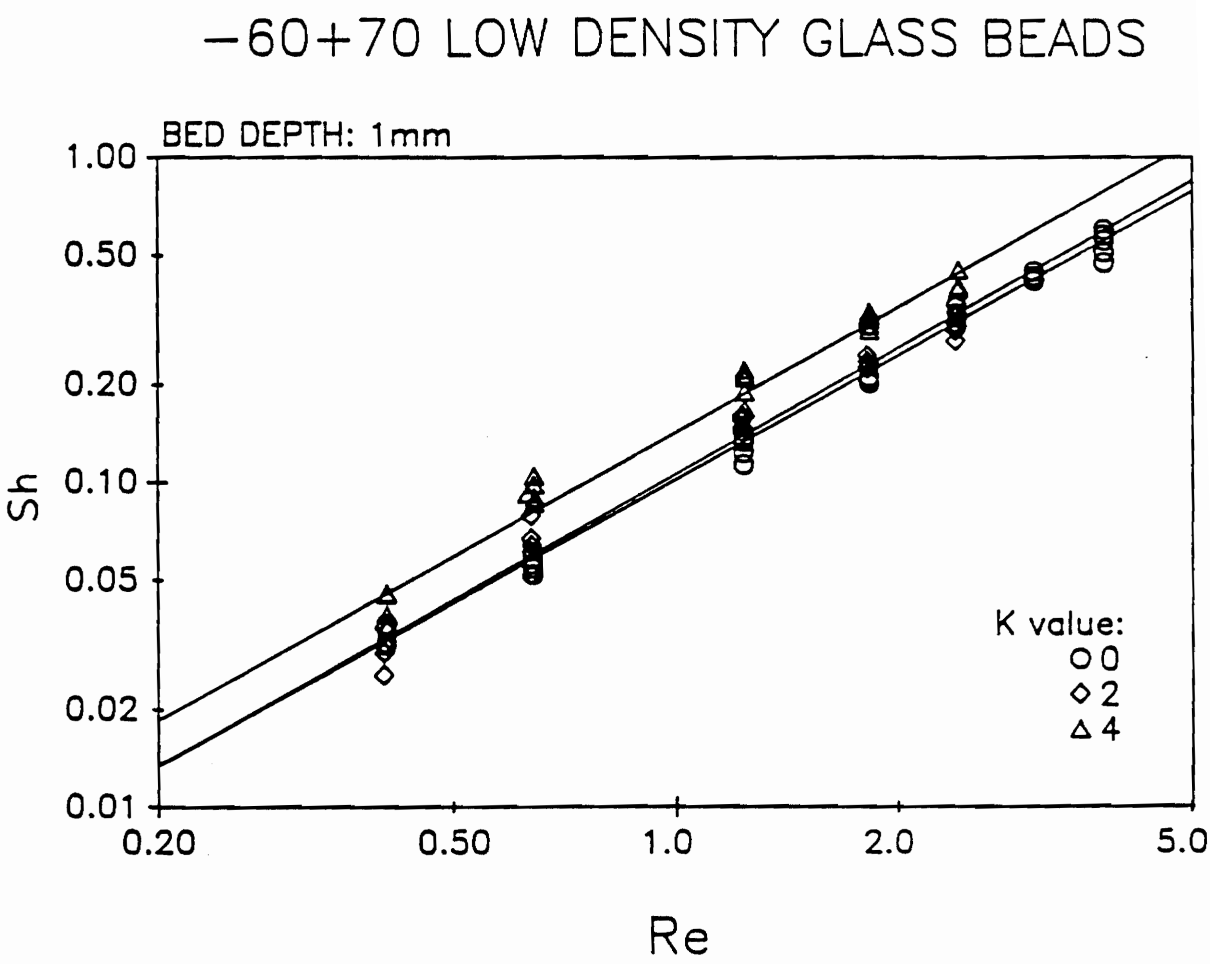


Figure 38. -60 + 70 Low density glass beads; bed depth = 1 mm.

Table 33. -100 + 140 Master Beads; K = 4, bed depth = 1 mm.

-100+140 MASTER BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (1/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	18.3	17.9	1.3170	3.185E-02	7.141E-04	0.093	1.372E-02
2	18.2	17.9	1.3170	3.144E-02	6.839E-04	0.093	1.314E-02
3	18.2	17.9	1.3170	3.239E-02	7.566E-04	0.093	1.454E-02
4	18.1	17.8	1.3170	3.093E-02	6.661E-04	0.093	1.281E-02
5	18.1	17.8	1.3170	3.205E-02	7.499E-04	0.093	1.442E-02
6	18.0	17.7	3.1876	3.200E-02	1.860E-03	0.226	3.578E-02
7	18.0	17.7	3.1876	3.280E-02	2.036E-03	0.226	3.917E-02
8	17.9	17.7	3.1876	3.305E-02	2.096E-03	0.226	4.031E-02
9	17.9	17.6	3.1876	3.285E-02	2.115E-03	0.226	4.071E-02
10	17.9	17.6	3.1876	3.346E-02	2.277E-03	0.226	4.383E-02
11	17.8	17.5	5.0582	3.441E-02	4.237E-03	0.360	8.160E-02
12	17.8	17.5	5.0582	3.385E-02	3.934E-03	0.360	7.576E-02
13	17.8	17.5	5.0582	3.419E-02	4.111E-03	0.360	7.917E-02
14	17.7	17.5	5.0582	3.338E-02	3.705E-03	0.360	7.135E-02
15	17.7	17.5	5.0582	3.391E-02	3.966E-03	0.360	7.638E-02
16	17.6	17.4	9.7347	3.437E-02	8.440E-03	0.693	1.626E-01
17	17.8	17.5	9.7347	3.451E-02	8.263E-03	0.692	1.591E-01
18	17.8	17.7	9.7347	3.547E-02	8.717E-03	0.691	1.677E-01
19	17.9	17.8	9.7347	3.494E-02	7.812E-03	0.691	1.502E-01
20	17.9	17.7	9.7347	3.430E-02	7.460E-03	0.691	1.435E-01
21	18.0	17.8	14.4112	3.636E-02	1.404E-02	1.023	2.699E-01
22	18.0	17.9	14.4112	3.518E-02	1.149E-02	1.022	2.208E-01
23	18.0	17.9	14.4112	3.590E-02	1.262E-02	1.022	2.426E-01
24	18.1	18.0	14.4112	3.572E-02	1.186E-02	1.021	2.278E-01
25	18.1	18.0	14.4112	3.690E-02	1.390E-02	1.021	2.671E-01
26	18.5	18.3	19.0877	3.852E-02	2.037E-02	1.350	3.907E-01
27	18.5	18.4	19.0877	3.885E-02	2.042E-02	1.349	3.914E-01
28	18.5	18.3	19.0877	3.850E-02	2.032E-02	1.350	3.897E-01
29	18.5	18.4	19.0877	3.940E-02	2.218E-02	1.349	4.252E-01
30	18.5	18.3	19.0877	3.845E-02	2.016E-02	1.350	3.866E-01
31	18.6	18.4	24.3515	4.021E-02	3.226E-02	1.721	6.184E-01
32	18.6	18.4	24.3515	3.821E-02	2.377E-02	1.721	4.557E-01
33	18.6	18.4	24.3515	3.912E-02	2.710E-02	1.721	5.195E-01
34	18.6	18.4	24.3515	3.855E-02	2.494E-02	1.721	4.781E-01
35	18.6	18.4	24.3515	3.908E-02	2.696E-02	1.721	5.168E-01

Table 34. -100 + 140 Master Beads; K = 2, bed depth = 1 mm.

-100+140 MASTER BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	18.3	18.1	1.3170	2.680E-02	4.188E-04	0.093	8.021E-03
2	18.3	18.2	1.3170	2.720E-02	4.258E-04	0.093	8.151E-03
3	18.3	18.1	1.3170	2.676E-02	4.173E-04	0.093	7.993E-03
4	18.4	18.1	1.3170	2.626E-02	3.993E-04	0.093	7.649E-03
5	18.4	18.2	1.3170	2.731E-02	4.299E-04	0.093	8.231E-03
6	18.4	18.2	3.1876	2.883E-02	1.194E-03	0.226	2.285E-02
7	18.4	18.2	3.1876	2.788E-02	1.094E-03	0.226	2.095E-02
8	18.4	18.4	3.1876	2.857E-02	1.117E-03	0.225	2.137E-02
9	18.5	18.3	3.1876	2.758E-02	1.045E-03	0.225	1.999E-02
10	18.5	18.5	3.1876	2.932E-02	1.170E-03	0.225	2.237E-02
11	18.8	18.7	5.0582	3.102E-02	2.069E-03	0.357	3.951E-02
12	19.0	18.9	5.0582	3.149E-02	2.061E-03	0.356	3.932E-02
13	19.0	19.0	5.0582	3.129E-02	1.980E-03	0.356	3.775E-02
14	19.2	19.1	5.0582	3.176E-02	2.017E-03	0.356	3.843E-02
15	19.2	19.2	5.0582	3.202E-02	2.016E-03	0.356	3.841E-02
16	19.4	19.2	9.7347	3.416E-02	4.689E-03	0.684	8.932E-02
17	19.4	19.3	9.7347	3.292E-02	4.101E-03	0.684	7.807E-02
18	19.4	19.4	9.7347	3.532E-02	4.954E-03	0.684	9.427E-02
19	19.5	19.4	9.7347	3.412E-02	4.448E-03	0.684	8.463E-02
20	19.7	19.5	9.7347	3.359E-02	4.148E-03	0.683	7.888E-02
21	19.7	19.6	14.4112	3.481E-02	6.661E-03	1.011	1.266E-01
22	19.8	19.6	14.4112	3.502E-02	6.784E-03	1.011	1.290E-01
23	19.8	19.7	14.4112	3.545E-02	6.865E-03	1.010	1.304E-01
24	19.9	19.7	14.4112	3.505E-02	6.633E-03	1.010	1.260E-01
25	19.8	19.8	14.4112	3.561E-02	6.789E-03	1.009	1.289E-01
26	20.0	19.9	19.0877	3.586E-02	8.965E-03	1.336	1.702E-01
27	20.4	20.1	19.0877	3.723E-02	9.581E-03	1.334	1.817E-01
28	20.4	20.1	19.0877	3.605E-02	8.667E-03	1.334	1.643E-01
29	20.4	20.1	19.0877	3.656E-02	9.047E-03	1.334	1.715E-01
30	20.3	20.0	19.0877	3.661E-02	9.315E-03	1.335	1.767E-01
31	20.4	20.1	24.3515	3.852E-02	1.369E-02	1.702	2.595E-01
32	20.3	20.0	24.3515	3.743E-02	1.277E-02	1.703	2.422E-01
33	20.3	20.1	24.3515	3.753E-02	1.255E-02	1.702	2.378E-01
34	20.3	20.1	24.3515	3.764E-02	1.266E-02	1.702	2.401E-01
35	20.4	20.1	24.3515	3.740E-02	1.239E-02	1.702	2.350E-01

Table 35. -100 + 140 Master Beads; K = 0, bed depth = 1 mm.

-100+140 MASTER BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	18.4	18.0	1.3170	2.607E-02	4.000E-04	0.093	7.657E-03
2	18.4	18.1	1.3170	2.674E-02	4.168E-04	0.093	7.975E-03
3	18.4	18.2	1.3170	2.710E-02	4.220E-04	0.093	8.070E-03
4	18.5	18.3	1.3170	2.730E-02	4.212E-04	0.093	8.050E-03
5	18.5	18.3	1.3170	2.673E-02	4.004E-04	0.093	7.652E-03
6	18.5	18.4	3.1876	2.949E-02	1.214E-03	0.225	2.319E-02
7	18.5	18.4	3.1876	3.036E-02	1.314E-03	0.225	2.510E-02
8	18.6	18.4	3.1876	3.103E-02	1.399E-03	0.225	2.673E-02
9	18.6	18.4	3.1876	2.992E-02	1.262E-03	0.225	2.410E-02
10	18.6	18.4	3.1876	2.961E-02	1.226E-03	0.225	2.343E-02
11	18.6	18.5	5.0582	3.147E-02	2.260E-03	0.357	4.315E-02
12	18.8	18.6	5.0582	3.255E-02	2.442E-03	0.357	4.660E-02
13	18.8	18.6	5.0582	3.141E-02	2.193E-03	0.357	4.185E-02
14	19.0	18.7	5.0582	3.295E-02	2.472E-03	0.357	4.716E-02
15	19.0	18.7	5.0582	3.090E-02	2.046E-03	0.357	3.903E-02
16	19.1	18.9	9.7347	3.356E-02	4.790E-03	0.686	9.128E-02
17	19.4	19.3	9.7347	3.182E-02	3.732E-03	0.684	7.096E-02
18	19.5	19.3	9.7347	3.231E-02	3.893E-03	0.684	7.403E-02
19	19.6	19.5	9.7347	3.589E-02	5.080E-03	0.683	9.650E-02
20	19.6	19.5	9.7347	3.475E-02	4.586E-03	0.683	8.712E-02
21	19.8	19.8	14.4112	3.643E-02	7.292E-03	1.009	1.383E-01
22	20.1	20.0	14.4112	3.746E-02	7.578E-03	1.008	1.436E-01
23	20.2	20.0	14.4112	3.618E-02	6.779E-03	1.008	1.285E-01
24	20.2	20.1	14.4112	3.687E-02	7.013E-03	1.007	1.328E-01
25	20.2	20.2	14.4112	3.796E-02	7.501E-03	1.007	1.420E-01
26	20.4	20.3	19.0877	3.778E-02	9.523E-03	1.333	1.802E-01
27	20.4	20.3	19.0877	3.930E-02	1.087E-02	1.333	2.056E-01
28	20.3	20.3	19.0877	3.806E-02	9.756E-03	1.333	1.846E-01
29	20.3	20.3	19.0877	4.040E-02	1.202E-02	1.333	2.274E-01
30	20.3	20.2	19.0877	4.020E-02	1.216E-02	1.333	2.302E-01
31	20.8	20.7	24.3515	4.160E-02	1.513E-02	1.696	2.856E-01
32	20.6	20.5	24.3515	4.068E-02	1.479E-02	1.698	2.796E-01
33	20.6	20.5	24.3515	4.037E-02	1.439E-02	1.698	2.719E-01
34	20.6	20.5	24.3515	4.106E-02	1.532E-02	1.698	2.895E-01
35	20.6	20.6	24.3515	4.196E-02	1.613E-02	1.697	3.048E-01

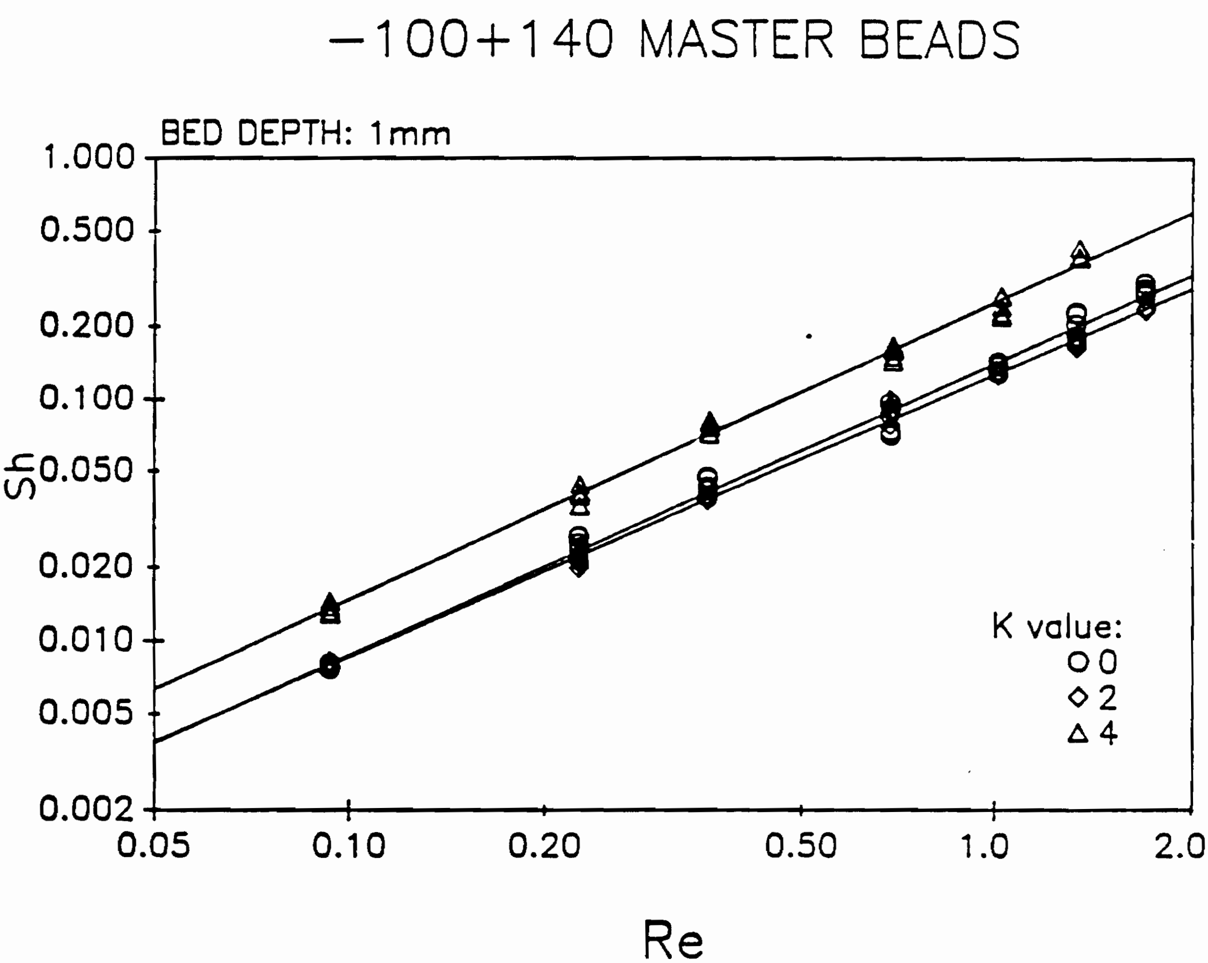


Figure 39. -100 + 140 Master Beads; bed depth = 1 mm.

Table 36. -100 + 140 Low density glass beads; K = 4, depth = 1 mm.

-100+140 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 4
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	23.2	23.1	3.1876	4.152E-02	8.382E-04	0.219	1.582E-02
2	23.2	23.0	3.1876	3.935E-02	7.522E-04	0.219	1.420E-02
3	23.1	23.0	3.1876	4.256E-02	9.127E-04	0.219	1.723E-02
4	23.1	23.0	3.1876	3.820E-02	7.027E-04	0.219	1.327E-02
5	23.1	23.0	3.1876	4.007E-02	7.850E-04	0.219	1.482E-02
6	23.1	23.0	5.0582	4.200E-02	1.399E-03	0.347	2.642E-02
7	23.1	23.1	5.0582	4.321E-02	1.473E-03	0.347	2.780E-02
8	23.0	23.0	5.0582	4.150E-02	1.357E-03	0.347	2.562E-02
9	23.0	23.0	5.0582	4.121E-02	1.334E-03	0.347	2.518E-02
10	23.1	23.0	5.0582	4.302E-02	1.490E-03	0.347	2.813E-02
11	23.1	23.0	9.7347	4.162E-02	2.632E-03	0.668	4.966E-02
12	23.0	23.0	9.7347	4.274E-02	2.818E-03	0.668	5.321E-02
13	23.1	23.0	9.7347	4.231E-02	2.745E-03	0.668	5.183E-02
14	23.0	23.0	9.7347	4.321E-02	2.902E-03	0.668	5.478E-02
15	23.0	23.0	9.7347	4.336E-02	2.929E-03	0.668	5.529E-02
16	23.1	23.1	14.4112	4.777E-02	5.616E-03	0.988	1.060E-01
17	23.1	23.1	14.4112	4.771E-02	5.593E-03	0.988	1.055E-01
18	23.1	23.1	14.4112	4.534E-02	4.794E-03	0.988	9.045E-02
19	23.1	23.2	14.4112	4.831E-02	5.663E-03	0.988	1.068E-01
20	23.2	23.2	14.4112	4.543E-02	4.705E-03	0.988	8.873E-02
21	23.2	23.1	19.0877	4.543E-02	6.387E-03	1.309	1.205E-01
22	23.2	23.1	19.0877	4.276E-02	5.411E-03	1.309	1.021E-01
23	23.2	23.2	19.0877	4.561E-02	6.302E-03	1.308	1.189E-01
24	23.5	23.3	19.0877	4.471E-02	5.819E-03	1.307	1.097E-01
25	23.6	23.4	19.0877	4.501E-02	5.788E-03	1.306	1.090E-01

Table 37. -100 + 140 Low density glass beads; K = 2, bed depth = 1 mm.

-100+140 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 2
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Pe	Sh
1	22.0	21.8	3.1876	3.125E-02	5.692E-04	0.220	1.081E-02
2	22.0	21.9	3.1876	3.236E-02	6.009E-04	0.220	1.141E-02
3	22.0	21.9	3.1876	3.071E-02	5.408E-04	0.220	1.027E-02
4	22.0	21.9	3.1876	3.175E-02	5.780E-04	0.220	1.097E-02
5	22.0	21.9	3.1876	3.163E-02	5.737E-04	0.220	1.089E-02
6	22.0	21.9	5.0582	3.409E-02	1.065E-03	0.349	2.022E-02
7	22.0	22.0	5.0582	3.445E-02	1.070E-03	0.349	2.030E-02
8	22.0	22.0	5.0582	3.443E-02	1.069E-03	0.349	2.028E-02
9	22.0	22.0	5.0582	3.265E-02	9.545E-04	0.349	1.811E-02
10	22.0	21.9	5.0582	3.184E-02	9.223E-04	0.349	1.751E-02
11	22.1	22.0	9.7347	3.473E-02	2.097E-03	0.672	3.980E-02
12	22.0	21.9	9.7347	3.361E-02	1.988E-03	0.673	3.774E-02
13	22.1	22.0	9.7347	3.443E-02	2.057E-03	0.672	3.903E-02
14	22.1	22.0	9.7347	3.611E-02	2.291E-03	0.672	4.347E-02
15	22.1	22.0	9.7347	3.583E-02	2.249E-03	0.672	4.268E-02
16	22.2	22.1	14.4112	3.546E-02	3.192E-03	0.994	6.053E-02
17	22.2	22.1	14.4112	3.583E-02	3.268E-03	0.994	6.197E-02
18	22.3	22.2	14.4112	3.595E-02	3.229E-03	0.994	6.121E-02
19	22.3	22.2	14.4112	3.641E-02	3.325E-03	0.994	6.302E-02
20	22.3	22.2	14.4112	3.744E-02	3.549E-03	0.994	6.728E-02
21	22.4	22.3	19.0877	3.819E-02	4.832E-03	1.316	9.155E-02
22	22.4	22.3	19.0877	3.863E-02	4.969E-03	1.316	9.415E-02
23	22.5	22.5	19.0877	3.802E-02	4.592E-03	1.314	8.691E-02
24	22.7	22.5	19.0877	4.032E-02	5.304E-03	1.314	1.004E-01
25	22.4	22.3	19.0877	4.008E-02	5.456E-03	1.316	1.034E-01

Table 38. -100 + 140 Low density glass beads; K = 0, bed depth = 1 mm.

-100+140 LOW DENSITY GLASS BEADS
VIBRATIONAL INTENSITY K= 0
BED DEPTH (mm)= 1

No	Tbed (C)	Tgas (C)	N2 FLOW (l/mn)	Pn (mmHg)	K (m/s)	Re	Sh
1	24.7	24.5	1.3170	3.901E-02	2.302E-04	0.090	4.322E-03
2	24.7	24.5	1.3170	3.703E-02	2.082E-04	0.090	3.908E-03
3	24.7	24.5	1.3170	3.725E-02	2.105E-04	0.090	3.952E-03
4	24.8	24.6	1.3170	3.936E-02	2.302E-04	0.089	4.320E-03
5	24.8	24.5	1.3170	3.734E-02	2.114E-04	0.090	3.969E-03
6	24.8	24.6	3.1876	4.118E-02	6.111E-04	0.217	1.147E-02
7	24.9	24.6	3.1876	4.198E-02	6.362E-04	0.217	1.194E-02
8	24.9	24.6	3.1876	3.768E-02	5.119E-04	0.217	9.604E-03
9	24.9	24.7	3.1876	3.890E-02	5.350E-04	0.216	1.003E-02
10	24.9	24.7	3.1876	3.895E-02	5.363E-04	0.216	1.006E-02
11	24.9	24.7	5.0582	4.093E-02	9.399E-04	0.343	1.763E-02
12	24.9	24.7	5.0582	4.288E-02	1.037E-03	0.343	1.944E-02
13	24.9	24.7	5.0582	4.144E-02	9.644E-04	0.343	1.809E-02
14	25.0	24.8	5.0582	4.492E-02	1.126E-03	0.343	2.110E-02
15	25.0	24.8	5.0582	4.255E-02	1.000E-03	0.343	1.875E-02
16	25.0	24.9	9.7347	4.231E-02	1.866E-03	0.660	3.497E-02
17	25.0	24.8	9.7347	4.244E-02	1.914E-03	0.660	3.589E-02
18	25.0	24.8	9.7347	4.141E-02	1.819E-03	0.660	3.409E-02
19	24.9	24.8	9.7347	4.681E-02	2.384E-03	0.660	4.469E-02
20	24.9	24.8	9.7347	4.475E-02	2.148E-03	0.660	4.026E-02
21	23.3	23.2	14.4112	4.021E-02	3.436E-03	0.988	6.494E-02
22	23.8	23.4	14.4112	3.815E-02	2.938E-03	0.986	5.546E-02
23	23.8	23.6	14.4112	4.148E-02	3.407E-03	0.985	6.425E-02
24	23.8	23.6	14.4112	3.939E-02	3.032E-03	0.985	5.718E-02
25	23.8	23.7	14.4112	4.042E-02	3.149E-03	0.984	5.935E-02
26	24.0	23.7	19.0877	4.196E-02	4.542E-03	1.304	8.561E-02
27	24.0	23.7	19.0877	3.790E-02	3.632E-03	1.304	6.846E-02
28	24.0	23.8	19.0877	4.148E-02	4.335E-03	1.303	8.168E-02
29	24.1	23.8	19.0877	4.384E-02	4.943E-03	1.303	9.312E-02
30	24.1	23.8	19.0877	4.329E-02	4.793E-03	1.303	9.030E-02

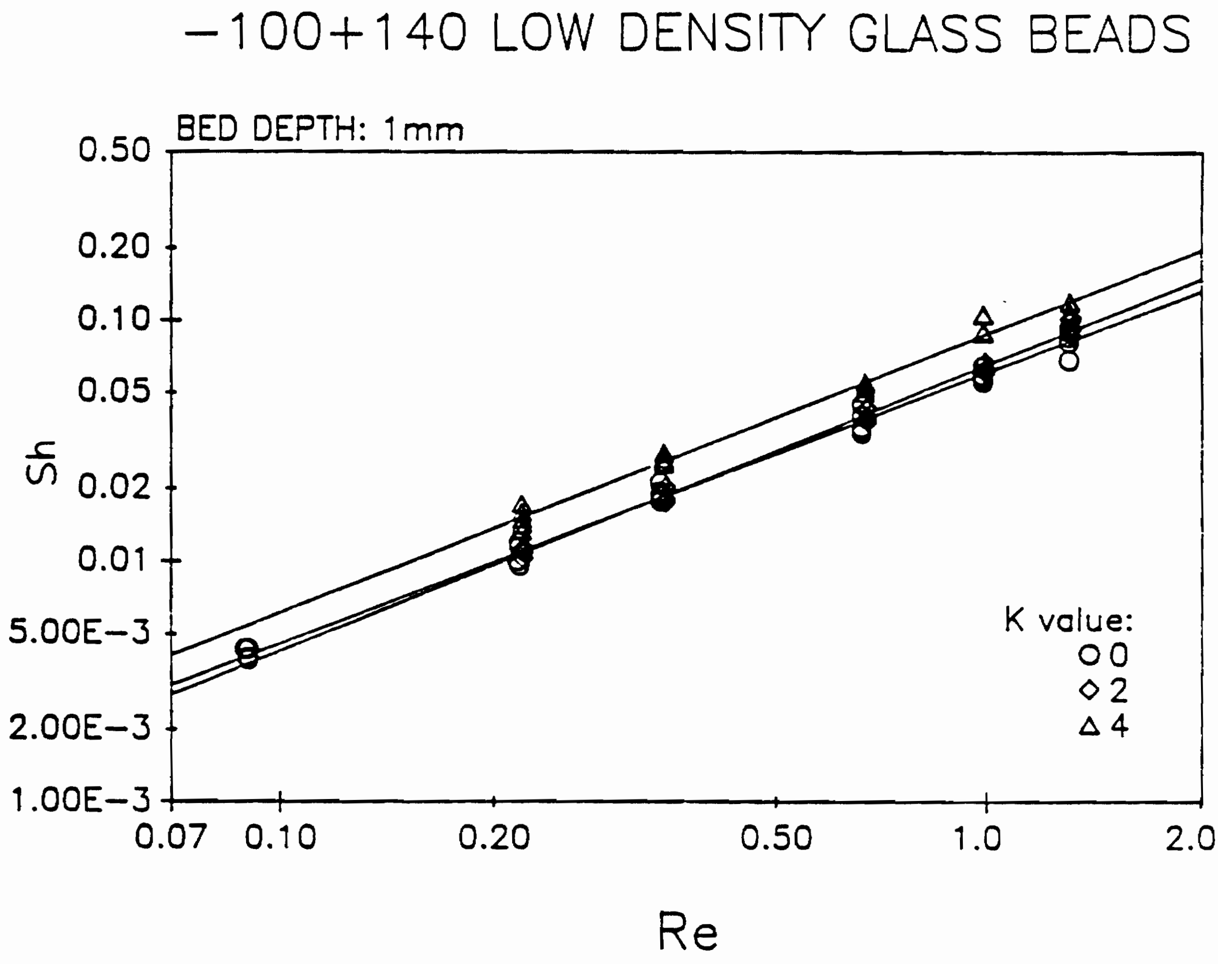


Figure 40. -100 + 140 Low density glass beads; bed depth = 1 mm.

Table 39. Synthesis of mass transfer results

$j_d = ARe^b$

Particle Type	Bed Depth (mm)	K	A	b
-16+30 Master Beads	24	4 2 0	0.035 0.34 0.24	0.410 0.392 0.301
	1	4 2 0	0.492 0.391 0.241	0.025 0.058 0.113
-16+30 low density glass beads	24	4 2 0	0.033 0.026 0.027	0.296 0.353 0.326
	1	4 2 0	---- 0.403 0.406	---- 0.118 0.166
-40+50 Master Beads	24	4 2 0	0.016 0.012 0.035	0.306 0.303 0.465
	12.7	0	0.01	0.338
	1	4 0	0.228 0.155	0.188 0.255
-60+70 Master Beads	1	4 2 0	0.162 0.118 0.102	0.281 0.277 0.254
-60+70 low density glass beads	24	4 2 0	0.015 0.011 0.008	0.400 0.330 0.327
	1	4 2 0	0.162 0.118 0.102	0.281 0.277 0.254
-100+140 Master Beads	1	4 2 0	0.190 0.096 0.107	0.235 0.173 0.212
-100+140 low density glass beads	1	2 0	0.403 0.406	0.118 0.167

Appendix D. Minimum Fluidization Velocity

The minimum fluidization velocity is determined by means of the pressure drop across the bed as described in the introduction. The pressure of the bed is measured by a M.K.S. INSTRUMENTS, Inc. model PDR.D.1 pressure transducer of 0 to 10 mmHg range. Since the pressure is taken at the bottom of the bed vessel, the pressure drop across the grid plate has first to be measured, and then substracted from the total pressure to determine the pressure drop of the particle bed only.

The above table gives the corresponding Reynolds number at the minimum fluidization velocity for each solid particles used. For the -16+30 Master Beads, the minimum fluidization velocity is at a higher flow rate than the range of measurement and thus, cannot be determined accurately.

Table 40. Minimum fluidization velocity.

Particle Type	U_{mf} (mm/s)	Re_{mf}
-16+30 low density glass beads	250	14
-40+50 Master Beads	54	1.60
-60+70 Master Beads	20	0.30
-60+70 low density glass beads	25	0.38
-100+140 Master Beads	17	0.14
-100+140 low density glass beads	13	0.11

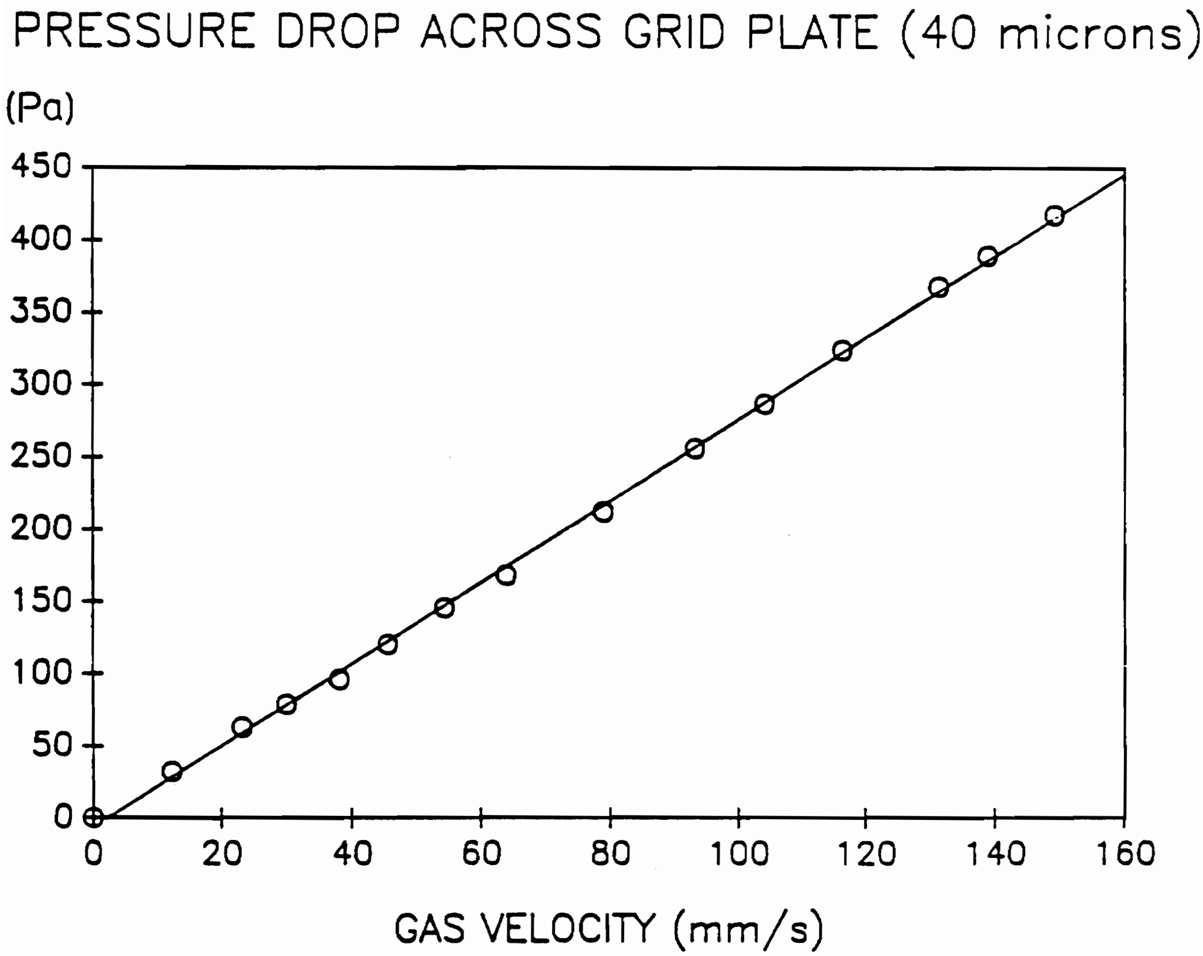


Figure 41. Pressure drop across grid plate.

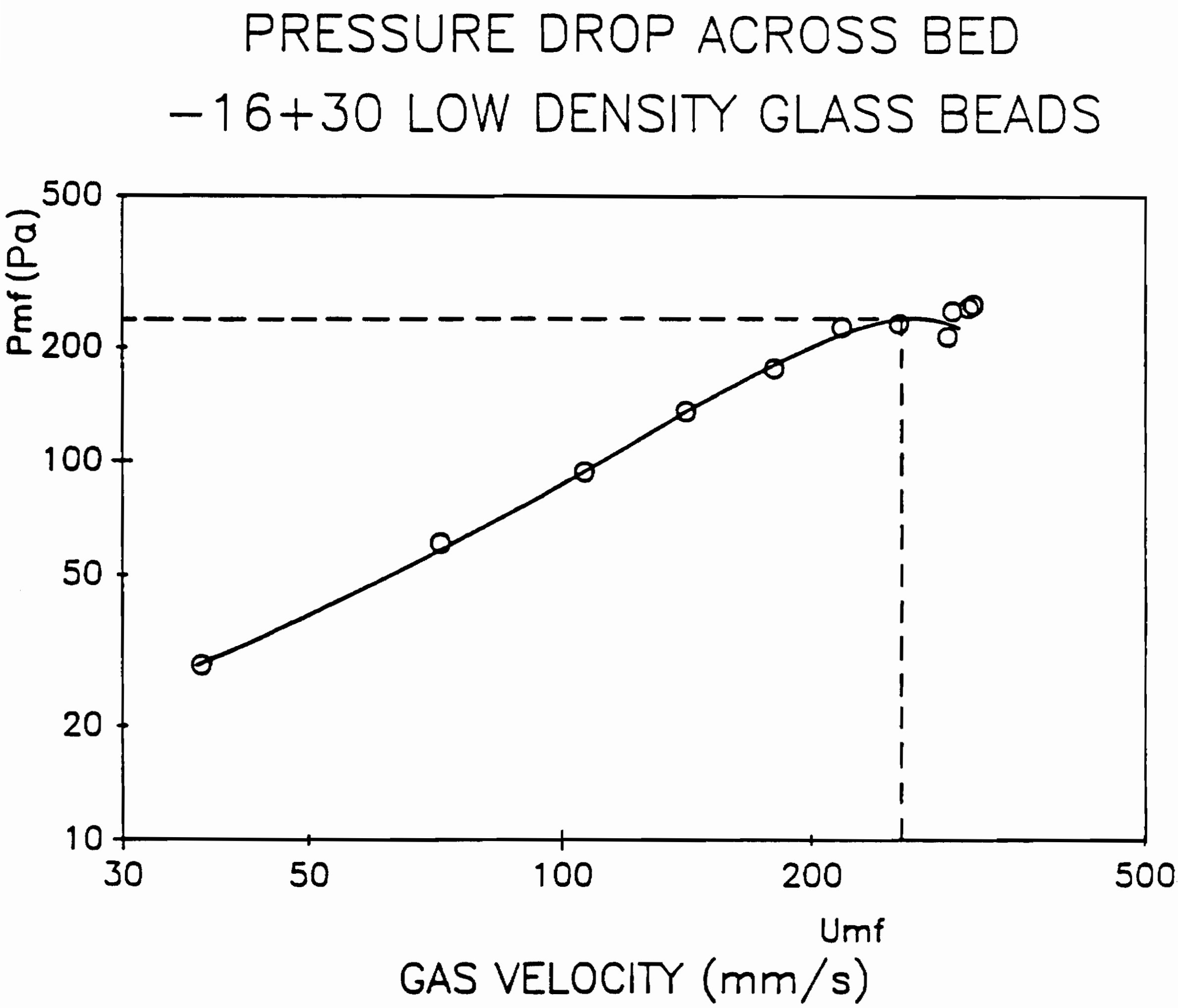


Figure 42. Minimum fluidization velocity; -16+30 glass beads.

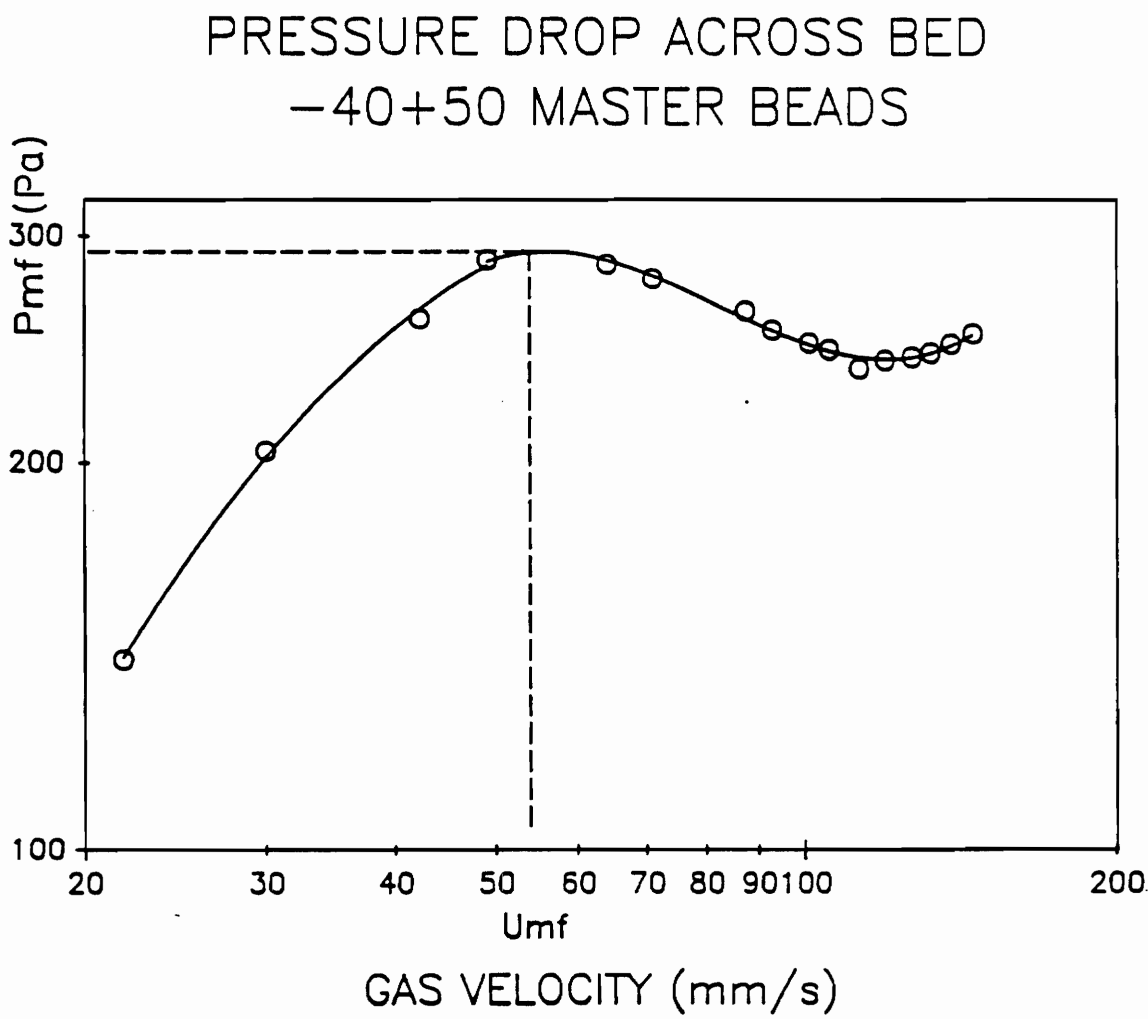


Figure 43. Minimum fluidization velocity; -40 + 50 Master Beads.

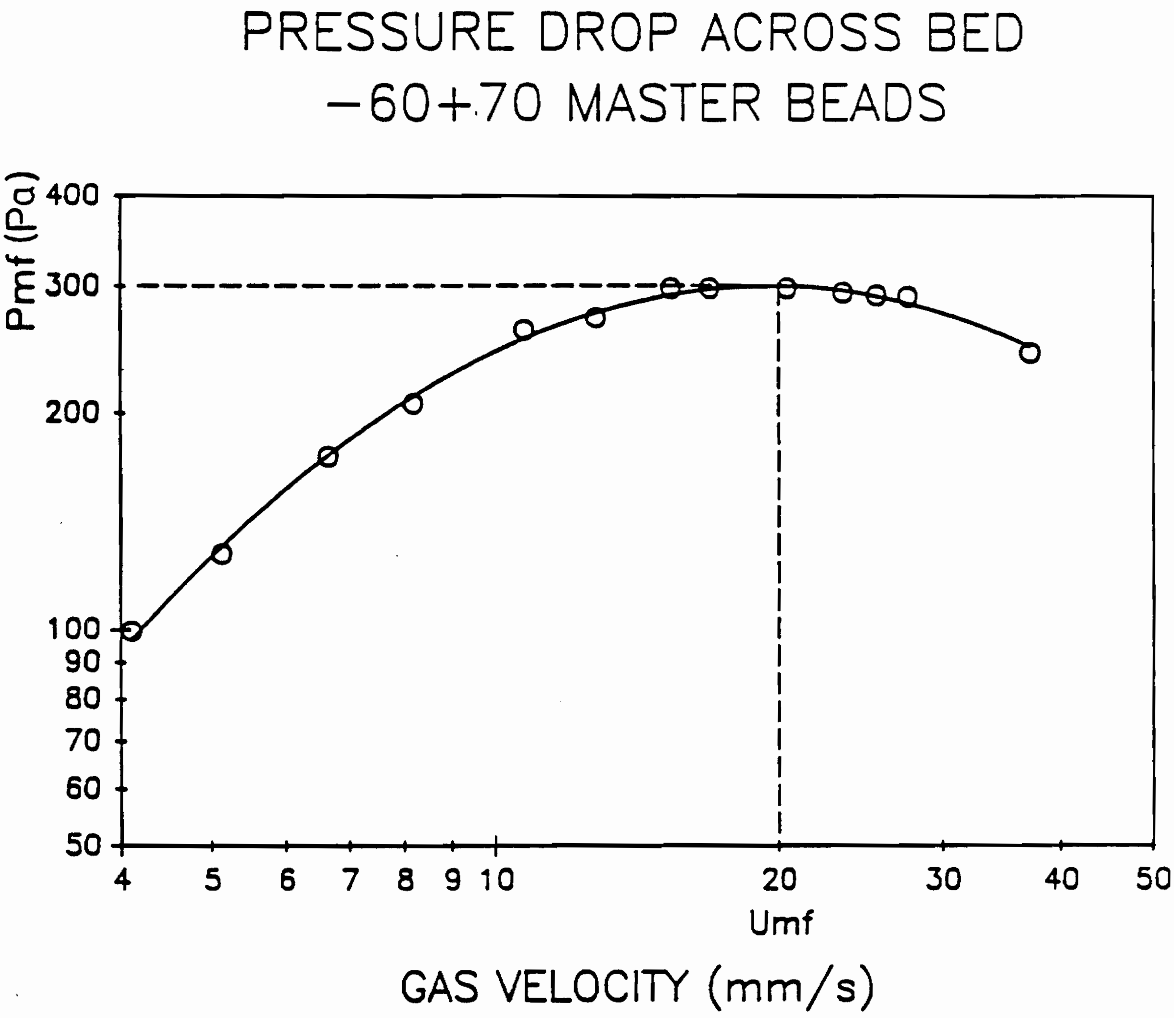


Figure 44. Minimum fluidization velocity; -60+70 Master Beads.

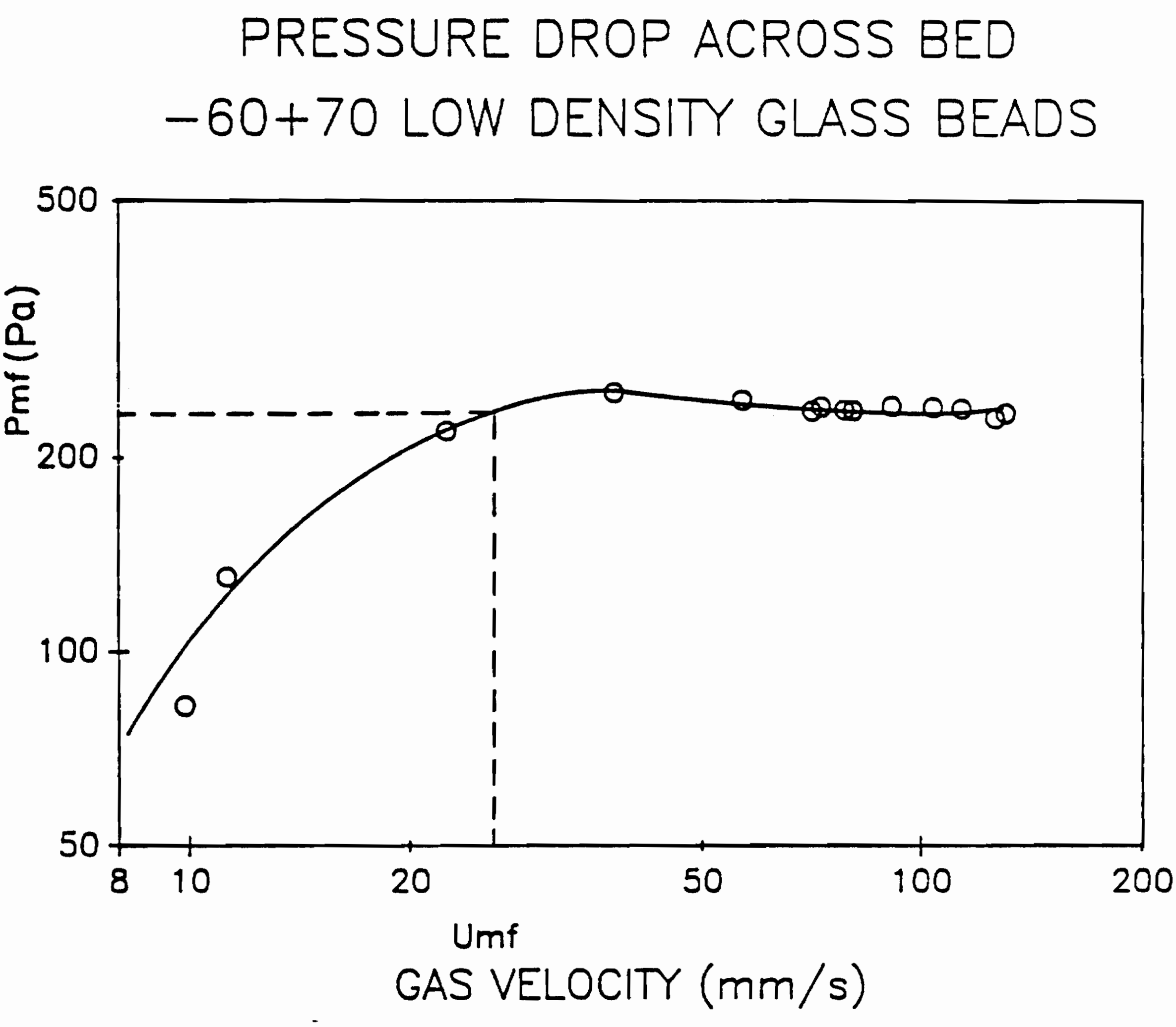


Figure 45. Minimum fluidization velocity; -60 + 70 glass beads.

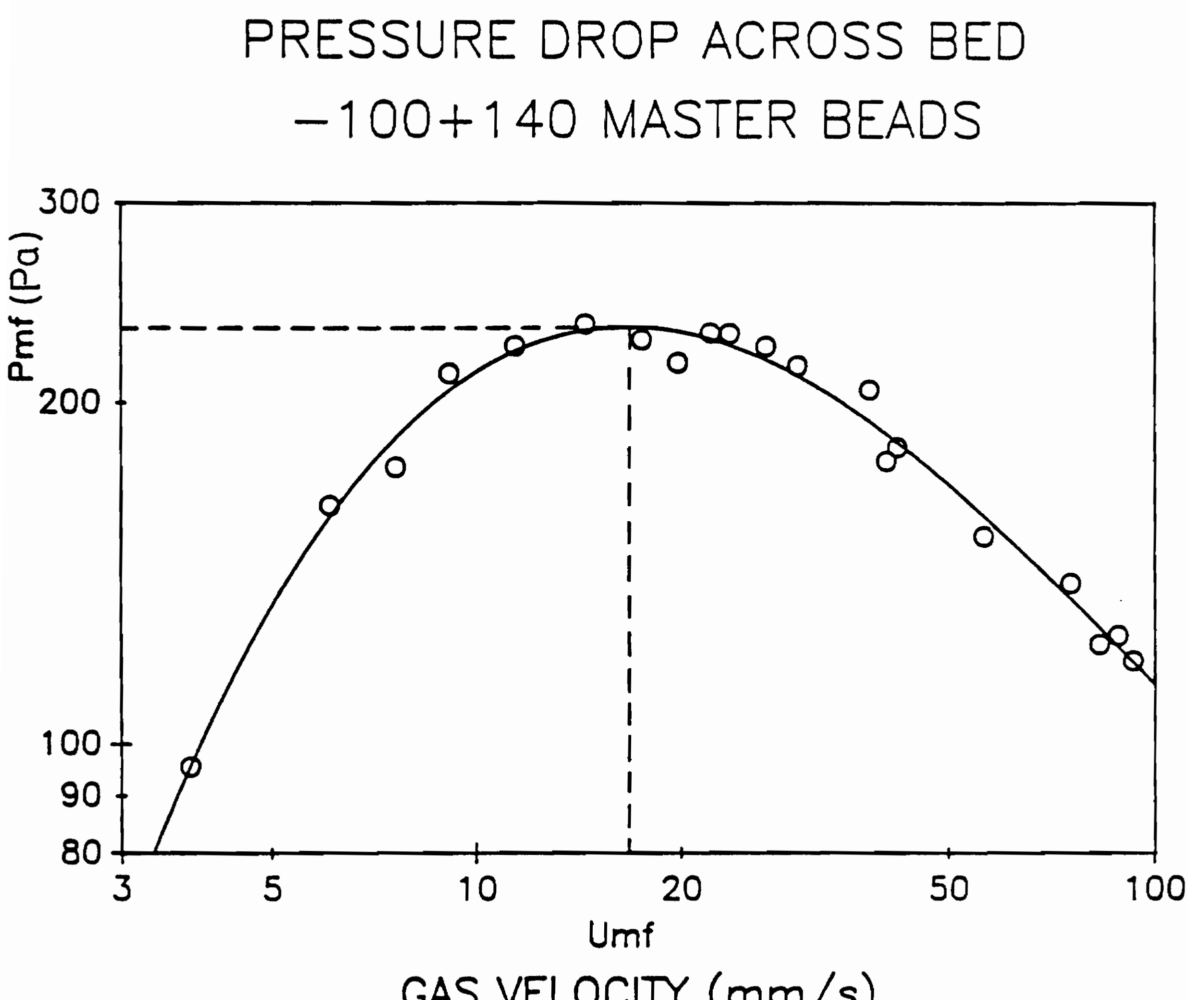


Figure 46. Minimum fluidization velocity; -100 + 140 Master Beads.

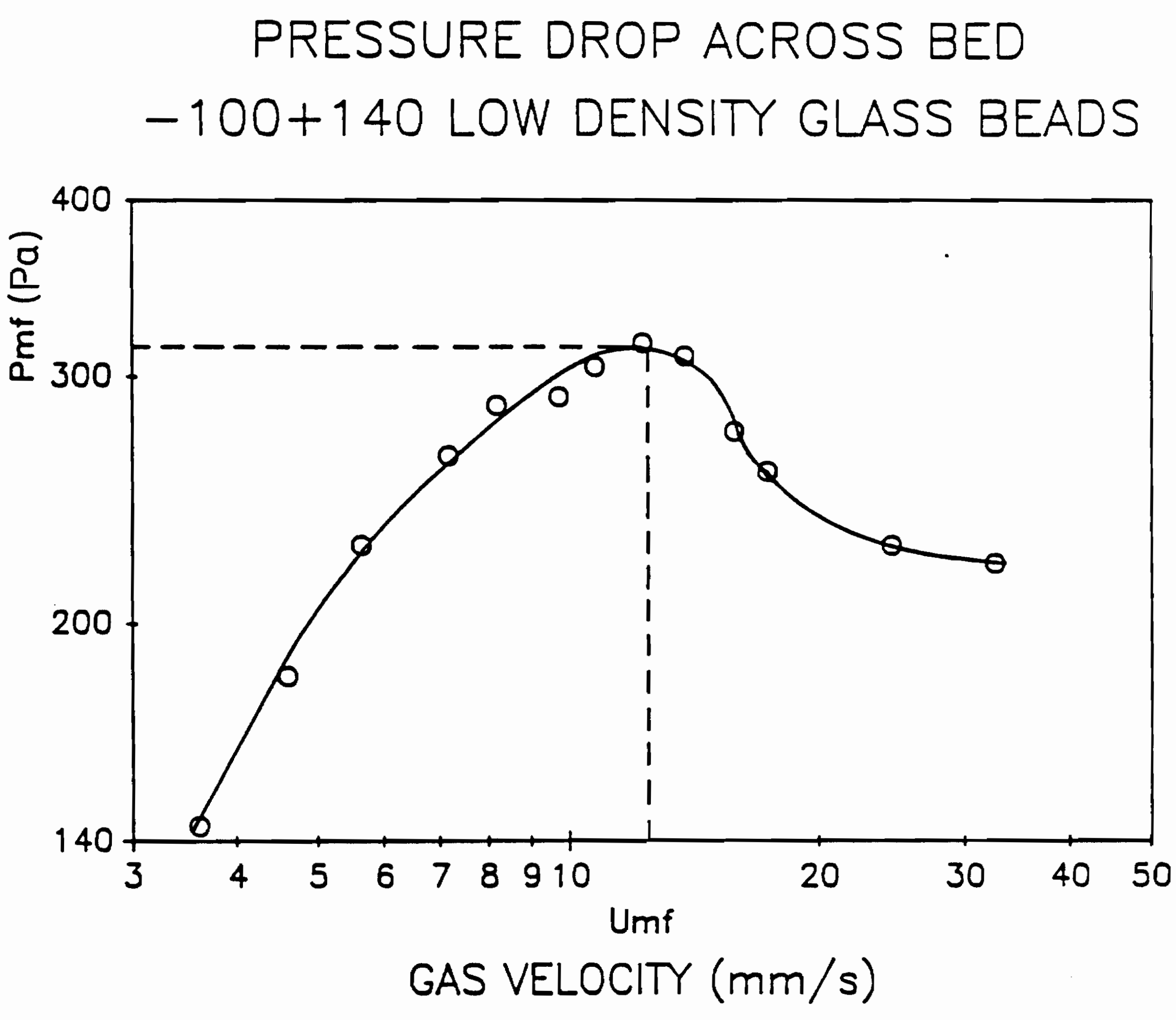


Figure 47. Minimum fluidization velocity; -100 + 140 glass beads.

Vita

The author was born on January 10, 1965 in Versailles, France. He took engineering classes at the Institut Universitaire de Technologie en Génie Thermique et Energie, Lorient, France. In March 1990, he received an engineer degree in "Génie Chimique" from Université de Technologie de Compiègne, France. He began his graduate studies at Virginia Polytechnic Institute and State University in August 1988 and completed his Master of Science in Chemical Engineering in February of 1990.

Christian E. Raison