FORCES ON OBJECTS IMMERSED IN FLUIDIZED BEDS

BY

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ABSTRACT

Internal baffles and other objects immersed in fluidized bed have a wide application in fluidized bed technology. For all applications, it is important to understand the forces exerted on these objects.

The forces on floating objects of various sizes and shapes were evaluated to calculate the effective density of the dense phase at three superficial gas velocities. It was found that the effective density under minimum fluidization conditions can be used to estimate the effective density of the particulate phase with respect to net buoyancy forces on immersed objects. More experimental data at high superficial gas velocities are needed before it can be determined with confidence whether differences between experimental effective densities at different gas flowrate are significant. Comparisons were made with results in a real liquid, and it was found that objects in a real liquid behaved in the same way as objects floating in the three-dimensional fluidized bed.

The pressure fluctuations caused by the passage of a bubble past horizontal tubes in a two-dimensional fluidized bed were measured using a pressure transducer. The pressures were measured for three tubes of 0.635 cm, 2.54 cm and 5.08 cm outside diameter. For the 0.635 cm and 2.54 cm tubes, all pressure curves had qualitatively the same shape. The net force versus time curve was found to have an approximately sine-wave shape with the maximum corresponding to the time when the bubble front reaches the bottom of the tube and the minimum to the time when the bubble rear reaches the bottom of the tube. Hence the tube tends to be pushed upwards and then downwards when a bubble passes. As the tube size increased, the frequency of bubble splitting on the tube increased. For a 5.08 cm outside diameter

tube, all the bubbles split as they hit the tube. It is apparent that there exists a critical tube size ($2.54 \text{ cm} < D_0 < 5.08 \text{ cm}$) where all bubbles of a given size split as they hit the tube directly.

RÉSUMÉ

Les chicanes et autres objets immergés dans un lit fluidisé ont un large domaine d'application dans la technologie des lits fluidisés. Dans toutes les applications il est important de connaître les forces exercées sur ces objets.

On a évalué les forces exercées sur des objets de tailles et formes variées, afin de calculer la densité apparente de la phase dense pour trois vitesses superficielles du gaz de fluidisation. On a trouvé que la densité apparente correspondant aux conditions d'apparition de la fluidisation peut être utilisée pour estimer la densité apparente de la phase particulaire par rapport aux forces d'Archimède exercées sur les objets immergés. D'autres données expérimentales à de plus larges débits gazeux seront nécessaires pour déterminer avec certitude si la densité apparente est une fonction du débit gazeux. On a fait des comparaisons avec des données relatives à un liquide réel, et on a trouvé que les objets plongés dans un liquide ont un comportement similaire aux objets flottant sur un lit fluidisé à trois dimensions.

On a mesuré avec un capteur de pression les fluctuations de pression causées par le passage d'une bulle autour de tubes horizontaux insérés dans un lit fluidisé bidimensionnel. Trois tubes de diamètres externes 0.635 cm, 2.54 cm, et 5.08 cm ont été utilisés. Les variations de pression présentaient qualitativement la même forme pour les tubes de 0.635 et 2.54 cm. La force nette représentée en fonction du temps laissait apparaître une courbe de forme approximativement sinusoïdale, le maximum correspondant à l'instant où le sommet de la bulle atteignait le dessous du tube et le minimum à l'instant où l'arrière de la bulle atteignait la

bas du tube. Ainsi le tube subissait une force ascendante puis descendante lorsqu'une bulle passait. La fréquence de dédoublement des bulles au contact du tube augmentait avec la taille du tube. Pour un tube d'un diamètre externe de 5.08 cm, toutes les bulles se dédoublaient au contact du tube. Il semble qu'il existe une taille de tube critique, comprise entre 2.54 et 5.08 cm, pour laquelle toutes les bulles d'une taille donnée se brisent lors du contact direct avec le tube.

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Chapter 1

INTRODUCTION

Practical fluidized beds commonly contain heat transfer tubes, baffles, or other objects. In strongly endothermic or exothermic reactions, substantial amounts of heat need to be transferred to or from a bed of fluidized particles so that internal tubes may be a necessity as surfaces of heat exchange. These and other fluidized beds are commonly equipped with diplegs, nozzles, probes, or structural members which are immersed in the bed for cooling, heating, coating, drying, processing, quenching, etc. In other applications, large pieces of coal or other materials may be added to a bed of smaller, more dense ash particles (e.g. in coal combustion or gasification processes). The types of baffles and other submerged objects and their influence on fluidized beds have been reviewed by Grace and Harrison (12, 13).

In all applications, the designer not only has to study the optimum-geometry, orientation, and size of the internal surface, but he has also to be aware of the forces exerted on the objects. For example, it is well known that the forces which arise from the bubbling motion of a heterogeneous fluidized bed cause transverse vibrations which can lead to tube failure. In this work, we are particularly interested in the vertical forces caused by passage of a rising bubble on horizontal tubes. It is also important to know the forces acting on floating objects of various sizes and shapes in a fluidized bed, and the conditions under which a lighter object may be floated at the bed surface.

In the next chapter, the forces on objects floating in a three-dimensional fluidized bed are considered. The objective of this part of

the work is to see whether the laws governing the floating of bodies in real liquids can be adapted to apply to objects at the surface of a fluidized bed.

In Chapter 3, the local and net instantaneous forces acting on horizontal tubes are studied using a two-dimensional column and different tube diameters. The objective of this work is to obtain insight into the origin of tube vibrations in fluidized beds. Overall conclusions of the work are presented in Chapter 4.

Chapter 2

FORCES ON OBJECTS FLOATING IN FLUIDIZED BEDS

2.1 Introduction

The term "fluidization" arises because a bed of solid particles supported by upflowing gas or liquid is given certain qualities which resemble properties of real fluids. One of the well-known properties is that it is possible to float objects at the bed surface, just as it is possible to float logs, boats or other objects on the surface of a real liquid.

Although this effect is well-known, there appears to have been no systematic work regarding the conditions under which objects will float on top. It seems reasonable to expect some sort of Archimedes-type buoyancy force and work designed to test this force is described in this chapter. The work is relevant to objects floated at the surface (e.g. large chunks of coal added to beds of heavier particles) and to forces acting on fixed immersed objects like heat transfer surfaces.

2.2 Theoretical Basis

Objects floating freely in real liquids under steady state conditions are subjected to two forces equal in magnitude, but opposite in direction. They are the buoyancy force, F_B and a gravitational force, F_G . At equilibrium, $\vec{F}_B + \vec{F}_G = 0$ (1)

From Archimedes' principle:

$$F_B = V_F \rho_F g \quad (2)$$

while the magnitude of the gravity force is simply:

$$F_G = M g \quad (3)$$

where V_F is the volume of liquid displaced by the object, ρ_F is the liquid density, g the gravitational acceleration and M the mass of the object.

In a fluidized bed with the superficial velocity, U , set at the minimum fluidization value, U_{mf} , the pressure drop across any section of the bed should equal the weight of the fluid and the particles in this section divided by the cross-sectional area. In practice, small deviations occur due to local channelling and particle-particle contacts. The pressure at a distance h below the surface of a bed is given very nearly by:

$$p = p_s + \frac{\rho_p(1 - \epsilon_{mf})Ahg}{A} + \frac{\rho_f \epsilon_{mf} Ahg}{A} \quad (4)$$

where p_s is the pressure at the bed surface, A is the bed cross-sectional area and ϵ_{mf} the voidage at minimum fluidization. Hence for $\rho_p \gg \rho_f$ (gas fluidized beds):

$$p - p_s \approx \rho_p(1 - \epsilon_{mf})gh \quad (5)$$

Hence the bed acts like a liquid with an effective density of

$$(\rho_{eff})_{THEO} = \rho_p(1 - \epsilon_{mf}) \quad (6)$$

As for a real liquid, an object floating in a fluidized bed must be subjected to a buoyancy force, F_B , and a gravitational force, F_G . In addition, there will be a drag force, F_D due to flow of fluidizing gas around the object. Under steady state condition,

$$\vec{F}_B + \vec{F}_G + \vec{F}_D = 0 \quad (7)$$

with $F_B = \rho_{eff} V_F g \quad (8)$

and $F_G = Mg \quad (9)$

where ρ_{eff} is the effective density of the dense phase determining the buoyancy force.

It can readily be demonstrated that the drag force term, F_D , will in general be much smaller than the gravity terms for objects whose dimensions are much larger than the dimensions of the particles. For a single particle in the incipiently fluidized bed, the particle's weight (neglecting buoyancy ^{in air}) is balanced by the drag on the particle, i.e.

$$F_{DP} = C_{DP} \frac{\rho_f u_{mf}^2}{2} \frac{\pi}{4} d_p^2 = \rho_p \frac{\pi}{6} d_p^3 g \quad (10)$$

The drag on the object floating in the bed is

$$F_{DO} = C_{DO} \frac{\rho_f u_{mf}^2}{2} S_o \quad (11)$$

while the weight of the object is

$$F_G = \rho_o H_o S_o g \quad (12)$$

where S_o is the maximum cross-section of the object in a horizontal plane

and $H_o = V_o/S_o$ is a characteristic height of the object.

Hence
$$\frac{F_{DO}}{F_G} = \frac{C_{DO} \rho_f u_{mf}^2}{2 \rho_o H_o g} \quad (13)$$

which after substitution from Equation (10) can be rewritten

$$\frac{F_{DO}}{F_G} = \frac{2 C_{DO} \rho_p d_p}{3 C_{DP} \rho_o H_o} \quad (14)$$

But ρ_p and ρ_o are expected to be of the same order. Drag coefficients

for particles in an assembly depend strongly on the local voidage, and

also on particle shape and the Reynolds number. The Reynolds number of the

object will be many times larger than that for a particle because of the

much larger characteristic dimensions; the local voidage may also be larger

judging from the observations of Glass(9). Hence one would expect

$C_{DO} < C_{DP}$, but all that is necessary to the argument here is that C_{DO} not

be much greater than C_{DP} which is certainly true. Hence, since $d_p \ll H_o$

for any object in question, it is clear that the drag force is much less

than the gravity force. Equation (7) may therefore be written as

$$\vec{F}_B + \vec{F}_G \approx 0 \quad (15)$$

To put this another way, if a bed was made up of an assembly of objects identical to the one in the bed, the superficial velocity, $(U_{mf})_0$ required to fluidize these objects would be very much greater than U_{mf} for the small particles which actually make up the bed. But only for $U = (U_{mf})_0$ would drag forces balance gravity forces. Since $U_{mf} \ll (U_{mf})_0$, we conclude that drag forces are very much less than sufficient to balance gravity forces on their own.

Equations (8), (9) and (15) yield:

$$\rho_{eff} = \frac{M}{V_F} \quad (16)$$

It is not clear whether or not the effective dense phase density, ρ_{eff} , will be the same as $(\rho_{eff})_{THEO}$ determined from Equation (6). Discrepancies could arise due to: (a) non-uniform voidage effects around an immersed object. For example, Glass and Harrison (9) showed that there tends to be a region of increased voidage on the underside of an immersed object, and it might be expected that this would increase the buoyancy force on such an object. (b) Voidage variations may also be associated with bubbles. The voidage of the dense phase for $U > U_{mf}$ has been shown to be close to ϵ_{mf} except near bubbles where an increase in voidage (of order 10%) has been found to occur (18).

2.3 Experiments

2.3.1 Size and Shape of Objects used in the Experiments

Objects of three shapes were chosen: a sphere, cylinders and rectangular parallelepipeds (Fig.2.1). The dimensions of the objects were as follows:

- (a) Sphere: This was a 3.81 cm outside diameter hollow sphere. Its mass could be varied by pouring different amounts of copper powder into

Fig. 2-1: Shapes and Configuration of Objects

opening

Sphere

Cylinder

Rectangular

Parallelepiped

Fig 2.1a : Shapes of objects

1-Without copper powder inside the object

2-With copper powder inside the object

Rectangular parallelepiped:

$$h_1 = 1, 1.5, 2.5, 3, 4, 4.5, 5, 5.5, 71n$$

$$h_2 = 2.5, 4, 4.5, 5, 5.5, 71n$$

Cylinder:

$$h_1 = 2, 3.51n$$

$$h_2 = 51n$$

Fig.2-1b: Configuration of Objects

the sphere through an opening at the top. The perimeter line passing through the center of the opening was graduated in 0.1 cm intervals to make possible measurement of the arc length of the sphere segment submerged in the fluidized bed.

(b) Cylinders: These were cylinders with outer diameter of 3.81 cm . Two such cylinders were constructed with lengths of 5.08 cm and 7.62 cm respectively. The two parts could be used separately with a disc sealing the open end, or they could be attached end to end to make a 12.70 cm long cylinder. Graduated scales were again affixed to the cylinder to allow measurement of the height of the cylinder submerged in the fluidized bed.

The mass of the cylinders could again be changed by adding different amounts of copper powder. The copper layer could be fixed by inserting a disc whose diameter is the same as the inside diameter of the cylinder onto the top surface of the copper powder layer.

(c) Rectangular parallelepipeds: These were hollow rectangular parallelepipeds closed at one end like the cylinders. The cross-sectional area was 14.50 cm square. The lengths were 2.54 cm , 3.81 cm 7.62 cm and 10.16 cm .

The rectangular parallelepipeds were graduated in the same way as the cylinder. The mass of the rectangular parallelepiped could be changed in the same manner as described above. Different lengths could also again be achieved by capping off individual rectangular parallelepipeds or attaching them end to end.

2.3.2 Fluidized Bed:

The work described in this chapter was carried out in a three-dimensional fluidized bed of diameter 45.72 cm and height 99 cm. The total

assembly is shown schematically in Fig. 2.2. The distributor was a perforated sintered plate. The particles in the bed were coarse sand with the sieve analysis given in Table 2.1 and mean size, $\bar{d}_p = 291 \mu\text{m}$. The minimum fluidization velocity, U_{mf} , was 7.0 cm/sec as shown in Fig. 2.3. The voidage of the dense phase at incipient fluidization, ϵ_{mf} , was 0.40 and the theoretical effective density, $(\rho_{eff})_{THEO}$, was 1.48 g/cm^3 . The bed was operated at three different superficial velocities, $U = 7.5 \text{ cm/sec}$, 8.7 cm/sec and 10.3 cm/sec , corresponding to 1.08 , 1.24 and $1.47 \times U_{mf}$ respectively.

2.3.3 Experimental Procedure

An amount of copper powder was added through the opening of the object. For the cylinders and the rectangular parallelepipeds, the copper powder layer was fixed and the object was closed as described in Section 2.3.1. The mass of the object was measured using a balance (OHAUS-ACCURACY $\pm 0.005\text{g}$). Next the object was placed at the middle of the bed surface, pushed gently downwards and released. The arc length of the sphere or the height of the object of other shapes submerged in the bed was measured visually after equilibrium had been achieved ($> 5 \text{ mns}$). For the cylinders and parallelepipeds, data was taken only when opposite ends of the object had the same reading.

At high superficial gas velocities, $1.24 U_{mf}$ and $1.47 U_{mf}$, the particles in the bed were thrown upwards at the bed surface, as observed by Roche (27) and sat on the top of the object; when this happened, the particles were swept away manually and the reading was taken only when there were almost no particles on the top of the object. The experiments at high superficial velocities therefore became tedious and time-consuming large heights of the objects had to be used and smaller amounts of experi-

Fig.2-2: Schematic flow diagram of three-dimensional fluidized bed

Table 2-1: Size distribution of coarse sand

Opening(micron)		WT% in range, x_i
Upper limit	Lower limit	
	420	9
420	297	41
297	210	31
210	149	14
149	105	4
150	74	1

Mean size, $\bar{d}_p = \sum x_i d_{pi} = 294 \mu m$

Fig.2-3: Determination of the minimum fluidization velocity.

mental data compared with the $1.08 U_{mf}$ case were taken because of this tendency for particles ejected from the bed surface to sit on the objects.

The volume of the dense phase displaced by the sphere was calculated by using a mathematical table for sphere segments (22). For other shapes, the volume was calculated by taking a product of the measured height and the cross-sectional area of the object.

2.4 Experimental Results

The experimental results for each shape at three different velocities are presented in Tables 2-2, 2-3 and 2-4. The volumes of dense phase displaced was plotted versus the mass of the objects, and a straight line, forced through the origin, was fitted by the least-squares method. The plots are shown in Figs. 2-4, 2-5 and 2-6. For each shape of object, the difference between the theoretical effective density and the experimental effective density was quite small as shown in Table 2-5. In order to determine whether the experimental effective densities differ significantly from the theoretical effective density, the t -distribution was used to test the significance of differences at the 1% level (2). As shown in Table 2-6, except for the rectangular parallelepiped at $U = 1.08 U_{mf}$, the differences between the experimental values and the theoretical value were insignificant. The experimental effective densities at different velocities and at different shapes were also used to form a new set with a grand mean, $\bar{x}_m$, calculated from

$$\bar{x}_m = \frac{\sum_{i=1}^{k} \bar{x}_i}{n_i} \quad (17)$$

where $\bar{x}_i$ is the experimental effective density for the i th set and n_i is the number of data sets. It was found that the difference between the grand mean and the theoretical value was not significant at all. Thus

Table 2-2: Experimental results for sphere in three-dimensional fluidized bed

U cm/sec	M g	S cm	V _F cm ³
7.5	11.03	2.5	8.97
	12.58	2.6	9.97
	15.79	2.8	11.98
	16.49	2.9	13.08
	20.00	3.0	14.12
	20.18	3.0	14.10
	22.89	3.2	16.16
	25.11	3.3	17.12
	28.15	3.5	18.99
	30.10	3.7	20.62
	33.26	3.9	22.00
8.7	12.12	2.5	8.97
	16.68	2.8	11.98
	22.2	3.1	15.27
	30.28	3.8	21.49
10.3	18.23	2.8	11.98
	21.15	2.9	13.13
	23.20	3.0	14.09
	25.41	3.3	17.11
	32.66	3.8	21.46

Table 2-3: Experimental results for cylinder in three-dimensional fluidized bed

Table 2-3a

U cm/sec	L cm	M g	H cm	V _F cm ³
7.5	7.62	26.44	0.89	15.41
	10.10	34.27	1.02	19.67
8.7	7.62	26.44	0.89	15.41
	10.10	34.27	1.02	19.66
10.3	7.62	26.44	0.89	15.41
	10.10	34.27	1.02	19.66

Table 2-3b L= 2.54 cm

U cm/sec	M g	H cm	V _E cm ³
7.5	11.44	17.62	8.69
8.7	11.44	17.62	8.69
10.3	11.44	17.62	8.69

Table 2-3b L= 10.16cm

U cm/sec	M g	H cm	V _F cm
7.5	112.68	6.86	78.20
	124.60	7.11	81.08
	126.75	7.37	83.98
	129.60	7.62	86.87
	132.40	7.75	88.35
	142.40	8.13	92.67
	146.85	8.38	95.56
	151.50	8.64	98.46
	157.61	9.40	107.14
8.7	112.18	6.73	76.73
	122.39	7.37	84.00
	132.27	7.75	88.30
	142.74	8.13	92.64
10.3	112.45	6.98	79.64
	122.32	7.24	82.74
	137.80	7.75	88.33
	143.05	8.38	95.56

Table 2-4: Experimental results for rectangular parallelepiped
in three-dimensional fluidized bed

U cm/sec	L cm	M g	H cm	V_F cm ³
7.5	2.54	13.02	0.63	9.22
	6.35	76.94	3.56	51.62
		83.81	3.81	55.32
		85.25	4.19	60.84
		99.07	4.83	70.05
		113.97	5.59	81.12
		134.70	4.83	95.53
	10.16	129.80	6.35	92.19
		132.40	6.10	88.49
		139.37	6.86	99.55
		143.97	7.11	103.24
		144.32	6.98	101.42
		154.13	7.62	110.61
		160.50	7.62	110.61
		164.52	8.00	116.14
		171.17	8.38	121.67
		174.20	8.38	121.65
		195.94	9.40	136.45
	17.78	216.19	10.41	151.17
		221.04	10.67	154.90
		228.24	10.92	158.54

Table 2-4(cont.)

U cm/sec	L cm	M g	H cm	V _E cm ³
7.5	17.78	235.12	11.43	165.80
		241.20	11.43	165.80
		245.80	11.94	173.29
		250.37	12.06	175.08
		255.38	12.45	180.67
		261.92	12.83	186.15
		265.65	12.57	182.55
		275.20	12.95	188.05
		284.90	13.46	195.41
		295.53	14.22	206.48
8.7	2.54	13.06	0.76	11.06
	6.35	72.38	3.30	48.22
		78.50	3.56	51.61
		88.82	3.94	57.16
		98.44	4.32	62.70
	10.16	134.49	6.35	92.18
		144.21	6.73	97.70
		154.92	7.37	106.91
		164.43	7.62	110.58
	10.29	181.37	8.13	118.00

Table 2-4(cont.)

U cm/sec	L cm	M g	H cm	V _F cm ³
8.7	10.29	189.72	8.64	125.39
		199.94	8.89	129.08
	17.78	224.85	10.16	147.44
		237.37	10.67	154.84
		246.52	11.05	160.39
		254.94	11.43	165.98
		267.17	12.19	182.56
		275.48	12.57	184.31
		286.05	12.70	184.31
		306.08	13.84	200.97
		319.70	14.35	208.27
10.3	6.35	75.35	3.05	44.24
		93.00	3.81	55.29
	10.16	113.54	4.83	70.04
		134.74	5.97	86.65
		155.45	7.37	106.91
		174.73	8.13	117.98
	10.29	198.91	9.14	132.78
	17.78	224.04	10.16	147.49
		245.85	11.43	165.89
		262.40	12.32	178.87
		274.84	12.95	187.99
		289.89	13.84	200.89

Fig.2-5:Effective density calculated from
cylinder

Fig.2-6: Effective density calculated
from rectangular parallelepipod

Table 2-5: Comparison of Theoretical effective density and Experimental effective densities.

Shape	ΔU cm/sec	$\frac{1}{\rho_{eff}}$ cm ³ /g	ρ_{eff} g/cm ³	$(\rho_{eff}) - (\rho_{app})$ g/cm ³	$G = \sqrt{\frac{1}{N} (\bar{V}_E - \bar{V}_E)^2}$	N	
Sphere	7.5	0.79	1.43	0.05	0.89	11	
	8.7	0.71	1.41	0.07	0.31	4	
	10.3	0.65	1.55	-0.06	0.59	5	
Cylinder L=7.62 cm	7.5	0.58	1.72	-0.23	0	I	
	8.7	0.58	1.72	-0.23	0	I	
	10.3	0.58	1.72	-0.23	0	I	
	l=10.16	7.5	0.57	1.74	-0.26	0	I
	cm	8.7	0.57	1.74	-0.26	0	I
	10.3	0.57	1.74	-0.26	0	I
7.5	0.67	1.49	-0.01	3.07	10	
	8.7	0.67	1.50	-0.01	1.95	4	
	10.3	0.67	1.49	-0.01	2.96	4	
Rectangular	7.5	0.70	1.43	0.05	2.12	36	
Parallelepiped	8.7	0.66	1.52	-0.04	2.72	21
10.3	0.67	1.48	0.00	4.25	12	

Table 2-6: Student t-test on the difference between the Theoretical Effective Density and the Experimental Effective Densities

Shape	1.08 U_{mf}	1.24 U_{mf}	1.47 U_{mf}
Sphere			
$ t $	1.14(NS)	2.28(NS)	2.40(NS)
$t_{,1\%}$	2.76	4.51	3.75
Cylinder			
$ t $	0.88(NS)	0.82(NS)	0.43(NS)
$t_{,1\%}$	2.81	4.54	4.54
Rectangular parallelepiped			
$ t $	9.86(S)	1.73(NS)	0.17(NS)
$t_{,1\%}$	2.44	2.53	2.72

9 Data Sets:

$$|t| = 0.05(NS)$$

$$t_{,1\%} = 2.9$$

$|t|$ = Absolute value of a statistic t calculated from the experimental data

$t_{,1\%}$ = Value of t with a probability $P=0.005$ of being exceeded in random sampling (1% level of significance)

S = Significant: $|t| > t_{,1\%}$

NS = Insignificant: $|t| < t_{,1\%}$

there is quite conclusive evidence that the differences between the experimental effective densities and the theoretical effective density were insignificant and the theoretical effective density can be used to estimate the effective density of the particulate phase under gently bubbling conditions. The t -test was also used to determine whether the experimental effective densities differ significantly at the 1% level. As shown in Table 2.7, for the sphere, the difference between the effective densities at $U = 1.08 U_{mf}$ and $1.24 U_{mf}$ was insignificant, but the difference between the values at $1.08 U_{mf}$ and $1.47 U_{mf}$ was significant. For cylinders having vertical orientation (i.e. axis of symmetry vertical), the difference between the data at $U = 1.08 U_{mf}$, $1.24 U_{mf}$, and $1.47 U_{mf}$ were not significant at all. For rectangular parallelepipeds orientated vertically, the difference between the values at $1.08 U_{mf}$ and at the other two velocities are significant. For the three shapes at $1.08 U_{mf}$, the density difference between the sphere and the rectangular parallelepiped was insignificant, while the difference between the sphere and the cylinder and between the cylinder and the rectangular parallelepiped were significant. Taking all these results together, it is inconclusive whether there is an effect of either object shape or superficial gas velocity on the effective density for the conditions studied.

The amount of experimental data at higher superficial velocities, $1.24 U_{mf}$ and $1.47 U_{mf}$ was quite small compared with that at $1.08 U_{mf}$ as mentioned above. More data are needed at higher velocities before it can be determined whether or not the effective densities at different velocities and at different shapes differ significantly with confidence.

In order to test how much of the difference in measured densities is due to experimental error, the experiments were repeated in a real

liquid. Bromobenzene was chosen as the liquid because its density, $\rho_f = 1.50 \text{ g/cm}^3$, is very near the theoretical density of the fluidized bed. The experimental results for the three shapes are tabulated in Tables 2-8, 2-9, 2-10. The relationship between the experimental submerged volume, V_p , and the mass of the objects, M , was fitted by least-squares method with the curves again forced through the origin. These results are plotted in Figs. 2-7, 2-8, 2-9. From Table 2-11, it was found that the differences of the densities measured from these three shapes were not significant at 1% level.

2.5 Stability of Floating Objects

Stability of floating objects with respect to tipping in real liquids is governed by the relative position of the center of gravity and the metacenter (16). Generally speaking, floating objects tend to tip over when displaced slightly from an equilibrium position if the center of gravity lies well above the liquid surface and the characteristic dimension of the object in the vertical direction is much greater than that in the horizontal direction.

In the present work, it was shown qualitatively that the same conclusion applies to objects floating in a fluidized bed. Two cases were considered:

(a) The original position of the object has the heavy end part at the bottom of the object (Fig. 2-1b). If the object was turned upside-down so that the heavy part was at the top, the object turned right back again to its original stable position.

(b) When the object was pushed down below the surface of the fluidized bed with any orientation, the object reappeared at the surface after some small period of time which depends on how deep the object was pushed down. Regardless of the original orientation, the final orientation

Table 2-7: Student t-test on the difference of the Experimental
Effective Densities

Shape and Velocity		$ t $	$t_{.1\%}$	Comment
S_1	S_2	0.38	3.01	NS
S_1	S_3	3.13	2.98	S
C_1	C_2	0.11	3.05	NS
C_1	C_3	0.23	3.05	NS
R_1	R_2	3.92	2.70	S
R_1	R_3	6.10	2.70	S
R_1	S_1	2.57	2.70	NS
R_1	C_1	4.86	2.70	S
S_1	C_1	2.89	2.86	S

S : Sphere

C : Cylinder

R : Rectangular Parallelepiped

1 : $1.08 U_{mf}$

2 : $1.24 U_{mf}$

3 : $1.47 U_{mf}$

Fig. 2-7: Bromobenzene density calculated from Sphere

Fig.2-8: Bromobenzene density calculated from Cylinder

Fig.2-9: Bromobenzene density calculated from Rectangular parallelepiped

Table 2-8: Experimental results for Sphere in Bromobenzene

M g	S cm	V _F cm ³
13.53	2.50	8.96
18.47	2.80	12.31
22.87	3.07	15.35
28.52	3.40	19.01
31.38	3.58	20.92
33.70	3.75	22.34
36.40	3.95	24.10

Table 2-9: Experimental results for Cylinder in
Bromobenzene

M g	H, cm	V _F cm ³
87.08	5.08	57.92
92.02	5.33	60.81
102.31	6.05	68.92
111.74	6.58	75.00
122.51	7.11	81.08
142.00	8.13	92.67
152.48	8.76	99.91
152.29	9.40	107.15

Table 2-10: Experimental results for Rectangular Parallelepiped
in Bromobenzene

M g	H cm	V_{F_3} cm ³
113.81	5.33	77.43
121.96	5.66	82.22
124.18	5.79	84.07
142.02	6.60	95.56
151.72	7.11	103.24
163.64	7.57	109.88
172.62	7.87	114.30
182.09	8.36	121.31
205.15	9.40	136.42

Table 2-II: Comparison of the difference of Measured Densities
of Bromobenzene by t-test

Shape		$ t $	$t, 1\%$	Comment
S	C	0.97	2.95	NS
S	R	2.44	2.92	NS
C	R	2.85	2.90	NS

at the bed surface was with the center of gravity at its lowest (most stable position).

The same behaviour as in the fluidized bed was observed for the objects in bromobenzene liquid. Hence the analogy between fluidized beds and real liquids appears to extend to the stability of objects floating at the surface under gentle fluidizing conditions.

Overall conclusions regarding the work presented in this chapter and suggestions for further work are presented in Chapter 4.

Chapter 3

FORCES ON HORIZONTAL TUBES

3.1 Introduction

The objective of the work described in this chapter was to measure the pressure caused by the passage of bubbles on the surface of horizontal tubes in a two-dimensional fluidized bed. This allows characterization of the forcing function causing tube vibrations in fluidized beds. As noted in Chapter 1, tubes are often immersed in fluidized beds as heat transfer surfaces or as baffles. Some vibration is probably desirable for creating favourable transfer conditions, but extreme vibrations can cause wear and rupture. Hence it is important to understand the forces involved.

3.2 Theoretical Basis and Previous Work

The motion of a bubble in an aggregative fluidized bed is analogous to the motion of a gas sphere through a real liquid of low viscosity (6). Single bubbles are commonly represented as spherically capped voids with concave indentations at their base.

This shape has been observed using X-ray photography (24) and is similar to the shape of large gas bubbles in liquids. There is, however, a significant difference between bubbles in real fluids and in fluidized beds. Surface tension is pronounced at the interface between gases and true liquids, whereas surface tension is generally taken to be zero at the interface between a gas bubble and the surrounding dense phase of a fluidized bed.

Reuter (24), (25) measured the pressure distribution around a freely rising bubble by means of a pressure transducer. He used "half bubbles" rising along a transparent wall of a rectangular bed. The bed was inclined slightly to the vertical so that the bubbles would rise along

the front wall. The motion of the bubbles was essentially three-dimensional. As shown in Fig. 3-1, Reuter considered a system of coordinates with its origin at the center of the bubble and moving with the bubble. The pressure drop in the particulate fluidized bed in the absence of the bubble is shown as a straight line described by the equation:

$$\frac{dP}{dz} = C \quad (1)$$

as discussed in Chapter 2.

The pressure within the bubble is approximately constant. At the top or front of the bubble, the pressure is higher than the pressure in the undisturbed fluidized bed at the same level. Conversely, in the lower part of the bubble, the pressure is lower than in the undisturbed fluidized bed at the same level. As one moves further away from the bubble, the pressure variation caused by the bubble was found to progressively disappear. At a certain distance from the bubble, both at the front and at the rear, the pressure is everywhere equivalent to the pressure of the undisturbed bed.

Fig. 3-2 shows the experimental pressure difference along with the curves corresponding to theoretical predictions of Davidson (6), Jackson (15) and Murray (19). Table 3-1 presents the theoretical expressions for pressure distribution around a bubble in two and three-dimensional fluidized beds (4).

Littman and Homolka (17) measured the pressure distribution around bubbles in a two-dimensional fluidized bed by means of a pressure transducer. The pressure curve has two maxima and two minima as shown in Figs. 3-3 and 3-4. Because of a lack of knowledge as to precisely where the bubble is when a given pressure recording is made, they had to rely on photographic studies of Rowe et al (29) and Partridge and Lyall (21) to

Fig. 3-1: Pressure distribution along the axis of symmetry of bubble.

Fig. 3-2: Dimensionless pressure difference between points on the vertical bubble axis and points in the same horizontal plane well removed from the bubble-three dimensional bubble

Fig.3-3: Experimental pressure curve along the axis of symmetry of a single bubble in two-dimensional fluidized bed- Run 23- Littman and Homolka.

Fig.3-4: Run 33- Littman and Homolka

Table 3-1: Expression for changes in the gas pressure due to the presence of a bubble. For more details, see Stewart(30)

Author	Two-dimensions	Three-dimensions
Davidson and Harrison(4)	$\pm \frac{1}{s}$ (Negative sign applied below the bubble)	$\pm \frac{1}{s^2}$
Jackson(15)	$\pm \frac{1}{4s^2} \left(1 - \frac{1}{2s^2} \right)$ (No solution below the bubble)	a) $\pm \frac{2}{9s^2} \left(2 - \frac{1}{s^3} \right)$ b) $\pm \frac{1}{2s^3} \left(2 - \frac{1}{s^3} \right)$
Murray(19)	$\frac{1}{4s^2}$ (No sign change below the bubble, hence invalid in this region)	$\pm \frac{1}{3s^3}$
Collins(4)	Above bubble: $\frac{1}{2} \left\{ s+0.54 - \sqrt{(s+0.54)^2 + 0.32} + \frac{3.5}{s-0.77 + \sqrt{(s+0.54)^2 + 0.32}} \right\}$ Below bubble: $-\frac{1}{2} \left\{ s-0.54 - \sqrt{(s-0.54)^2 + 0.32} + \frac{3.5}{s+0.77 + \sqrt{(s-0.54)^2 + 0.32}} \right\}$	

interpret some portions of the curve. Littman and Homolka assumed that the first maximum corresponds to the time when the air injection into the bed is cut off and the bubble has reached its maximum size; the second maximum was assumed to occur when the roof of the bubble reaches the pressure transducer tap. The first minimum was said to correspond to the instant when the rear of ^{the bubble} reaches the pressure transducer tap, while the second minimum occurs when the bubble begins to distort the upper surface of the bed. All experimental pressure curves had the same general shape as shown in Figs. 3.3 and 3.4, but they were not quantitatively reproducible. The slow pressure recovery behind the bubble was a notable and unexplained feature of their results.

The pressure distribution around two-dimensional and three-dimensional bubbles affects the motion of other bubbles, the motion of the particles and gas, and the forces on objects immersed in the fluidized beds. As a bubble approaches a fixed object in the bed, the pressure distribution on the object will in general differ from that in the absence of an approaching bubble. Hence, there will generally be a net force acting on the object. This is easily demonstrated experimentally if one observes floating objects, like those described in Chapter 2, being thrown aside by approaching bubbles. This is evidently related to tube vibrations in fluidized beds. In this work, we are particularly interested in the net force in the vertical direction on a horizontal tube. The experiments were carried out in ^a two-dimensional fluidized bed in order that the bubble sizes and trajectories could be measured unambiguously. Since the instantaneous magnitude of the force must change with position around the tube and with time, the experimental set up allowed surface pressures to be measured as a function of these two variables.

3.3 Experimental Equipment and Procedure

3.3.1 Fluidized Bed (Fig. 3.5)

The column was 245 cm high by 56 cm wide and roughly 1 cm thick. It was constructed entirely from acrylic polymer. The distributor is a 0.32 cm thick porous stainless steel plate. The bed has previously been described in detail by Chavarie (3).

The particles in the bed were glass microbeads of mean size $\bar{d}_p = 177 \mu\text{m}$ (see Table 3-2). The minimum fluidization velocity was measured to be 6.50 cm/sec (see Fig. 3-6), while the voidage at incipient fluidization was 0.41. Compressed air at 60 psig was passed through an air line filter, then regulated by means of pressure regulator before having its flowrate measured by a rotameter and being fed to the bed.

For single bubble injection experiments, a solenoid valve was placed at the outlet of a pressurized chamber of volume 3850 cm³. The pressure in the chamber was measured by a pressure gauge. The air fed to the chamber came from an air cylinder. The frequency and duration of gas injections were controlled reproducibly by an electric timer connected to the solenoid valve. By means of quick-connect fittings, the injector system was attached directly to a 0.32 cm hole, 12.7 cm above the distributor.

3.3.2 Pressure Transducer

A low-pressure transducer was used to measure the surface pressure during the passage of rising bubbles past horizontal tubes. This was a low pressure transducer (DISA Type 51D02-Pu2a) of capacitive type (Fig. 3.7). The capacitor consisted of a clamped diaphragm at zero potential and an electrode which was insulated from the transducer body and the diaphragm. The pressure to be measured caused the diaphragm to deflect, thus changing the capacitance between the diaphragm and the electrode. The pressure was

Fig.3-5: Schematic flow diagram of two-dimensional fluidized bed

1. Coaxial transducer plug
2. Connection branch for static calibration pressure
3. Housing, upper part, chromium-plated steel
4. Insulation, ceramic
5. Electrode, brass
6. Spacing ring, steel
7. Diaphragm, hardened steel
8. Packing ring, copper
9. Coolant
10. Cock plug
11. Connections for coolant (in and out)
12. Housing, lower part, chromium-plated steel.
13. Pressure channel

Fig. 3-7: DISA Low Pressure Transducer

Table 3-2: Measured size distribution of glass beads

Sieve opening, μm		WT%, x_i
Upper limit	Lower limit	
	417	0.02
417	297	0.03
297	212	2.72
212	149	90.42
149	50	6.81

$$\text{Mean size, } \bar{d}_p = \sum x_i d_{pi} = 177 \mu\text{m}$$

conveyed to the transducer through a pressure channel, 12. The three way cock, 10, was used for calibrating the transducer. The specifications of the type 51D02 low pressure transducer were as follows:

Diaphragm thickness, cm: 0.008
Pressure range, kgf/cm²: ± 0.020
Overload, kgf/cm²: 49
Diaphragm resonance, air F_{DG} , kHz: 2.50
Channel resonance, air 100°C, F_{CG} , kHz: 0.90
Temperature-dependent zero shift = approx. 0.01 pF/°C
Temperature-dependent sensitivity shift = 0.1%/°C
Calibrations: The transducer was provided with a connecting branch for calibration pressure and three-way cock. The pressure channel ahead of the diaphragm may therefore be connected either to the pressure to be measured or to the calibration pressure. The calibration air line was connected to a micromanometer which was used to calibrate the pressure difference as a function of voltage.

Total Capacitance of the transducer: approx. 20 pF
Active diaphragm capacitance = approx. 10 pF
Capacitance variations: At full transducer load, approx. 1 pF

The transducer was cooled by feeding distilled water at 30°C through the jacket. The cooling system consisted of a bath cooler, two thermostatic baths, and a quartz thermometer. The flow diagram of the cooling system is shown in Fig. 3-8. The cooling head of the cooler was immersed in the bath B_1 to be cooled, the water temperature T_1 of this bath was set at 26°C and the water in the bath B_1 was circulated through a coil of the bath B_2 by a pumping system of B_1 . The water temperature of the bath B_2 was set at $T_2 = 30^\circ\text{C}$. One pump section of the bath B_2 forced the water into the external system, passing through the coolant of the transducer; the other drew the water back into the circulator for retempering. These three units gave a maximum stability for the final setting temperature, T_2 . The accuracy of the temperature T_2 was doublechecked using a quartz thermometer. The temperature of the transducer was kept constant to within $\pm 0.01^\circ\text{C}$.

C: Bath Cooler

Neslab-Model PBC-2

Cooling Ability(20°C):
3500 Btu/hr

B₁: Thermostatic Bath

Neslab-Model TE9

Temperature Constancy: $\pm 0.005^\circ\text{C}$
Uniformity: $\pm 0.01^\circ\text{C}$

Maximum: 250°C

Pumping Volume: 130 gph

B₂: Thermostatic Bath

Neslab-Model TEV 70

Temperature Constancy:
 $\pm 0.002^\circ\text{C}$

Uniformity: $\pm 0.002^\circ\text{C}$

Maximum: 230°C

Volume: 70 liters

T: Quartz Thermometer

Hewlett- Packard

Model 280I A

Fig 3-8: Cooling System of the Pressure Transducer

The pressure transducer was used in conjunction with a tuning plug (Type 51C02), an oscillator (Type 51E02) which delivers a high-frequency signal whose frequency was inversely proportional to the pressure force, and a reactance converter (Type 51E01) which amplified the oscillator signal. Before being applied to the frequency-sensitive detector, the signal was fed through a limiter so that its amplitude is independent of the length of the cable between the oscillator and the converter. The frequency-sensitive detector rectifies the signal, following which the DC voltage variation is proportional to the pressure on the transducer system (Fig. 3-9).

Because the pressure changes caused by the passage of a bubble were relatively small, differential pressure measurement was used. This was achieved by blocking one of the two breather holes in the body of the transducer, and connecting the other to a chamber with a reference pressure which was set to match the pressure of the dense phase at the same level. This allowed more sensitive pressure measurements to be obtained.

3.3.3 Recorder

The Honeywell type 2106 Visicorder was used to record the output DC voltage proportional to the pressure difference. The Honeywell Visicorder was a mains-operated 14 channel oscillograph capable of recording signals without distortion ($\pm 2\%$) at up to 13 KHz. The recording paper speed could be varied from 0.5 to 200 cm per second. The ultraviolet light source produced legible records which became visible in office light or daylight in half a minute; the recordings could be made permanent with an aerosol developer. The galvanometers used were mirror type; sensitivity and damping features could be selected to suit the application. Two galvanometers were selected:

Fig.3-9: System of Measurement of DISA Pressure Transducer

(1) Galvanometer 1, a M-1000 fluid damped type, nominal undamped natural frequency 1000Hz; flat $\pm 5\%$ frequency response 0-600 Hz, required external damping resistance 3-100 Ω . Thus the response time of this galvanometer was less than two milliseconds. This galvanometer was used for recording the DC voltage variation caused by the mechanical influence on the transducer system.

(2) Galvanometer 2, a M-40. 120 Ω electromagnetic damped type; nominal undamped natural frequency 40 Hz; flat $\pm 5\%$ frequency response 0-600 Hz; required external damping resistance 120 Ω . This galvanometer was used to record the time when a bubble passed through a point, 7.6 cm below the center of the horizontal tube.

3.3.4 Amplifier

With galvanometers 1 and 2, a four channel DC amplifier, Honeywell Accudata 117, was used, taking care to damp the galvanometer using a 120 ohm resistance in the output circuit.

3.3.5 Photocell

The photocell was used with galvanometer 2 to record the time when a bubble passes and to allow synchronization. The photocell was placed 7.6 cm below the center of the horizontal tube. Facing the photocell at the back of the bed was a light source. The photocell was connected with a trigger switch to control the photocell sensitivity to the light reaching the photocell. This device was connected to a solid-state light and to the Honeywell visicorder as shown in Fig. 3.10. Where there was no bubble passing between the light source and photocell, the light intensity reaching the photocell was almost negligible. The solid-state light was then on and the DC voltage recorded by the Visicorder was at its minimum value. When a bubble passed the photocell, the light intensity increased causing the

Fig.3-10: Electrical Circuit and Geometry of Photocell.

solid-state light to shut off and the DC voltage to approach its maximum value. A mark was then recorded on the output trace from the recorder. When the bubble had passed this point, the light intensity reached the photocell returned to its minimum value, the solid-state light turned on again and the DC voltage returned to its minimum value. The output of the recorder therefore allowed not only the instantaneous pressure to be recorded as a function of time but also the mean bubble velocity to be measured and the traces to be interpreted with respect to the position of the bubble corresponding to different points on the pressure trace.

3.3.6 Horizontal Tubes

Three horizontal tubes were used. The 0.63 cm diameter hollow tube was constructed from steel. The other two hollow tubes were constructed from plexiglass with outside diameters of 2.54 cm and 5.08 cm. Each tube in turn was fixed between the front and rear walls of the bed, with its axis 101.6 cm above the distributor. As shown in Fig. 3.11, the pressure channel of the transducer passed through the hollow center of the tube. At the end of the pressure tube (on the outside of the cylinder), there was a screen to prevent particles from passing into the channel. Each tube could be turned manually to measure the pressure at different angular positions. Measurements were taken at angles of 0° , 30° , 60° , 90° , 120° , 150° , 180° to the vertical. The pointer allowed accurate positioning of the tube. Because the tubes were so short (~ 1 cm long) and rigidly supported, tube vibrations were negligible in the present equipment.

3.3.7 Ciné Photography

A Bolex reflex camera was used to measure the bubble properties. Film sequences were taken at 32 and 64 frames/sec. Frame by frame analysis of these films was performed manually: the image was focussed on a flat

Fig.3-II: Geometry of horizontal tube.

surface by means of mirrors. Both TRI-X and PLUS-X film were used. Clean images of the bubbles in the two-dimensional bed could be obtained readily using back-lighting.

3.4 Properties of Single Bubbles

A grid of 2.54 cm spacing taped on the outside of the front wall of the bed as well as easily identifiable features of the bed supports served as reference points and as surface area standards (see Fig. 3-12).

The superficial velocities used in the experiments ranged from 30% to 50% in excess of U_{mf} . This range was found to be optimal for maintaining stable bubbles. A consequence of this background flow rate was that growth of injected bubbles occurred with height both (a) at the expense of the dense phase (26), (28), and (b) due to coalescence with small bubbles in the bed (3), (14).

Only one size of bubble was studied in this work. The size range was limited by the fact that smaller bubbles tended to break up or to avoid the horizontal tube whereas larger ones must be considered slugs. Properties of single bubbles measured in this work were bubble area and velocity as functions of vertical position.

3.4.1 Bubble Area

The surface area of single bubbles was determined by a standard gravimetric analysis performed on paper cutouts of the bubble contours, traced from projected photographic images. Fig. 3-13 shows clearly that the bubble area increases with height above the distributor. In these experimental results, data are not included for bubbles undergoing splitting or those not rising on a vertical trajectory.

3.4.2 Bubble Velocity

The velocity of isolated bubbles was obtained by plotting the

Fig.3-12: Traces of the outline of an isolated bubble
rising through the two-dimensional fluidized bed.

Fig.3-I3: Growth of isolated bubbles with increasing height

nose and rear positions versus the number of photographic frames. The speed of the film and the slope of the curve formed by the midpoint of the above data pairs allowed calculation of the velocity as shown in Fig. 3-14. This procedure was used to measure the average bubble velocity throughout the interval of interest.

The measured velocities were compared with the velocities predicted by:

(a) Pyle and Harrison (23) for isolated bubbles, i.e.

$$U_B = 0.51g^{1/2}(A_B)^{1/4} \quad (2)$$

(b) Collins (5) for slug flow regime where the bubble velocity is no longer governed by bubble size, but solely by the dimensions of the bed, i.e.

$$U_{BS} = 0.357(gb)^{1/2} \quad (3)$$

where b is the half-width of the bed.

(c) Murray (19) for bubbles subject to wall effects but too small to be considered slugs

$$U_{BM} = \left(\frac{gb}{2\pi} \tanh \frac{\pi c}{2b} \right)^{1/2} \quad (4)$$

where c is half length of the bubble.

-Davidson (7), also for bubbles subject to wall effect,

$$U_{BO} = \left(\frac{gb}{2\pi} \tanh \frac{\pi c}{2b} \right)^{1/2} \left(1 - \frac{\tanh^2 \left(\frac{\pi c}{2b} \right)}{3} \right)^{1/2} \quad (5)$$

Table 3-3 shows that all measured velocities were lower than the slug velocities and the velocities for isolated bubbles, this would almost certainly be due to wall effects. The models for rising bubbles subject to wall effects give good agreement with experimental data with Murray's equation being more accurate, as found previously by Chavarie (3).

Fig.3-14: Typical rise of bubble.

Table3-3: Comparison between measured bubble rise velocities and predictions of various model

Y	A_B	R_B/b	c	U_B	U_{BS}	U_{BCM}	U_{BCD}
cm	cm ²		cm	cm/sec	cm/sec	cm/sec	cm/sec
76.0	594.7	0.92	13.7	41.5	59.2	45.6	44.9
80.6	596.7	1.00	17.3	48.1	59.2	45.4	44.5
79.5	537.6	0.93	13.2	47.1	59.2	44.4	43.6
74.3	552.1	1.04	15.1	47.0	59.2	43.6	42.8
77.2	603.9	0.98	13.9	40.8	59.2	44.9	44.0

3.5 Experimental Results

Three sizes of tubes were studied in this work and pressure differences were measured at seven angular positions around the tube. The bubbles were observed visually to eliminate those which did not rise on a vertical trajectory or those which were undergoing splitting and to include only those which passed through the tube without division.

All pressure curves had qualitatively the same shape with two maxima and one minimum. However, the experimental data were scattered and the time between the bubble reaching the photocell and the second maximum fluctuated. This could be caused by two factors:

- (a) The bubbles themselves may have different sizes, shapes, and velocities from bubble to bubble, e.g. due to interaction with small bubbles as they rose in the bed (the distribution of small bubbles being more or less random).
- (b) In the fluidized bed, particles can be found inside bubbles, raining through from the top. The signal from the photocell depends on the light intensity reaching it. Depending on the concentration of the particles near the front of the bubble and the velocity of the bubble, the maximum DC voltage recorded from the photocell may occur before or after the maximum of the pressure curve. Because the recordings from the photocell were ambiguous, photographic analysis was needed. From the film sequences and the pressure traces for the 0° orientation, it was found that the second maximum occurred when the front of the bubble reached the front of the tube for the 0° position. At other angular positions, it was assumed that the second maximum occurred when the bubble reached this position. The relative times from position to position were determined by photographic analysis.

3.5.1 Results for 0.64 cm Diameter Tube

Five pressure traces were taken at each position. The experimental pressure-time curves are shown in Figs. 3-15 to 3-21. It was observed that the first maximum occurred when the bubble was injected into the bed as found by Littman and Homolka (17) and discussed earlier. The difference between the shape of the pressure-time curves in this work and in that of Littman and Homolka was that only one minimum^{was} recorded, this minimum occurring when the rear of the bubble reached the front of the tube. Two or more minima were recorded only when the bubble split as it passed through the tube.

The mean experimental pressure difference between the front and the rear of the bubble at the 0° position was compared with the pressure difference predicted by Davidson (6), Jackson (15), Murray (19) and Collins (4) (see Section 3-1). Some correspondence might be expected since the 0.64 cm tube is very much smaller than the equivalent bubble diameter (13.5 cm). The experimental trace was between the values predicted by Collins and Murray, about double the value predicted by Jackson and about half the value predicted by Davidson.

The net vertical pressure force at time t can be calculated by integration, i.e.

$$\frac{F_t}{L} = 2R \int_0^\pi P_{i,t} \cos \theta_i d\theta_i \quad (6)$$

where F_t/L is force per unit tube length at time t and $P_{i,t}$ is pressure measured at angular positions, θ_i at time t

The net vertical pressure-force versus time curve is presented in Fig. 3-22. Integration was carried out numerically using the library subroutine QSF provided by the McGill computer system.

Fig.3-15a : Typical traces at different angular position
from the visicorder

- Angular position = 0° (Front stagnation point)

- Angular position = 30°

- Angular position= 60°

- Angular position = 90°

- Angular position= 120° .

- Angular position= 150°

- Angular position = 180°

Fig.3-15b: Pressure versus time curves at different angular position for 0.635cm tube.

Fig.3-15C: Pressure-time curve at 0° position for 0.635cm tube.

Fig.3-I6 : Pressure-time curves at 30° position for 0.635cm tube

Fig.3-17 : Pressure-time curves at 60° position for 0.635 cm tube.

Fig.3-18 : Pressure-time curves at 90° position for 0.635cm tube

Fig.3-19 : Pressure-time curves at 120° position for 0.635cm tube.

Fig.3-20 : Pressure-time curves at 150° position for 0.635cm tube.

Fig.3-2I : Pressure-time curves at 180° position for 0.635 cm tube.

Fig.32x: Net pressure-force versus time curves for 0.635cm tube and 2.54cm tube.

Fig.3-23a: Typical traces at different angular position
from the visicorder:

- Angular position = 0° (Front stagnation point)

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- Angular position = 30°

- Angular position= 60°

- Angular position= 90°

- Angular position=120°

- Angular position= 150°

- Angular position = 180°

Fig.3-23b: Pressure-time curves at different angular position for

2.54cm tube

Fig.3-23c: Pressure-time curves at 0° position, for 2.54cm tube.

Fig.3-24: Pressure-time curves at 30° position for 2.54cm tube.

Fig.3-25: Pressure-time curve at 60° position for 2.54cm tube.

Fig.3-26: Pressure-time curves at 90° position for 2.54cm tube

Fig.3-27: Pressure-time curves at 120° position for 2.54cm tube.

Fig.3-28: Pressure-time curves at 150° position for 2.54 cm tube.

Fig. 3-29: Pressure-time curves at 180° position for 2.54cm tube.

Fig. 3-30: Pressure-time curves at 0° position for 5.08cm tube-
Original size bubble.

Fig.3-31: Pressure-time curves at 0^0 position for 5.08cm tube-

Large size bubble.

3.5.2 Results for 2.54 cm Tube

The same behaviour was observed for the 2.54 cm tube as for the smaller tube, except that the frequency of bubble splitting as bubbles hit the tube seemed to increase. The pressure versus time curves are shown in Figs. 3-23 to 3-30 and the net vertical pressure force versus time curve appears in Fig. 3-22.

3.5.3 Results for 5.08 cm Tube

All bubbles underwent severe splitting as they hit the tube. Some typical-time curves are shown in Fig. 3-31.

The size of the bubbles was increased in order to achieve stable bubbles. To do this the pressure in the pressurized chamber was increased to double the original value, but stable bubbles could still not be obtained. Some pressure-time traces for this case are shown in Fig. 3-32. Cloete (8) did experiments with the same tube size in a 1.27 cm thick two-dimensional fluidized bed and reported the same phenomenon, i.e., he found that in all cases, the effect of the obstacle was to break up bubbles into two or more smaller bubbles.

It was apparent that there existed a critical tube size ($2.54 \text{ cm} < D_o < 5.08 \text{ cm}$) where all bubbles split as they hit the tube directly.

The experimental results for the horizontal tubes are summarized in the next chapter along with some suggestions for future work.

Chapter 4

DISCUSSION, CONCLUSIONS AND SUGGESTED FUTURE WORK

4.1 Conclusion

4.1.1 Steady Force on Floating Objects

It has been shown in Chapter 2 that spherical, cylindrical and parallelepiped objects can float on the surface of gently fluidized beds as on the surface of real liquids. The amount of dense phase displaced by a floating object is governed by Archimedes' law, where, within the accuracy of the experiments, the density of the displaced dense phase may be taken as the density of the bed under minimum fluidizing conditions. It has been shown that drag forces on floating objects due to interstitial gas is insignificant providing that the scale of the object is very much greater than the scale of the particles comprising the bed.

The experiments were inconclusive with respect to whether there is a significant effect of object shape (sphere, cylinders of different lengths, parallelepipeds of different lengths) or of superficial gas velocity (1.08, 1.24 and 1.47 U_{mf}) on the effective density of the fluidized bed governing the immersed depth of floating objects. Experiments at the higher superficial velocities were made difficult by the tendency of particles to splash onto the top surface of the floating object so that the amount of data obtained in these cases was limited. For engineering purposes, however, it is generally possible to assume $\rho_{eff} = \rho_p(1 - \epsilon_{mf})$. It also seems likely that for U well in excess of U_{mf} , one can expect at least three situations with respect to floating:

- (a) For very light objects (i.e. $\rho_o \ll \rho_{eff}$), especially for object shapes such that particles cannot sit on the surface

(e.g. tetrahedron with angle greater than angle of repose of the particles), the object should always stay on the surface.

- (b) For objects with $\rho_o < \rho_{eff}$, but such that particles can pile up on the upper surface, it is expected that the objects should spend periods at the bed surface, while splashed particles collect on the top, interspersed with periods of immersion.
- (c) For $\rho_o \gg \rho_{eff}$, the object is expected to go straight to the bottom.

It is not known whether there is a fourth class of objects which would circulate entirely within the bed, resting neither at the top nor the bottom.

4.1.2 Transient Forces on Fixed Submerged Tubes

Pressure forces on fixed horizontal tubes immersed below the surface of a fluidized bed have been measured and reported in Chapter 3. Special attention has been focussed on forces associated with the passage of single bubbles of known dimensions. For small size tubes of 0.63 cm and 2.54 cm outside diameter, all pressure versus time curves had qualitatively the same shape and the pressure traces did not change greatly with angular position. The net vertical force curves for these two tubes also had the same shape, but the magnitude of the vertical force is larger for the 2.54 cm tube because the force is proportional to the tube diameter.

As shown in Fig. 3-22, the net force versus time curves have an approximately sine-wave shape with the maximum corresponding to the time when the bubble front reaches the front of the tube and the minimum to the time when the bubble rear reaches the front of the tube. Hence the tube tends to be pushed upwards and then downwards when a bubble passes. In

these experiments, the frequency of injected bubbles was adjusted so that the pressure curves of successive bubbles were independent of one another. Any vibrations in the present experiments were negligible because of the short length (~ 1 cm) and rigidity of the tubes used. In freely bubbling fluidized beds, where many bubbles are present at one time, tubes would be expected to vibrate with an amplitude that depends on:

- The nature of the fluidized beds, i.e., the type of the particles, the bed dimensions, the operating superficial gas velocities, etc. These properties determine the bubble size and frequency.
- The position and the orientation of the tubes in the fluidized beds.
- The shape, diameter and length of the tubes.
- The material of construction, the thickness of the tubes and their means of support as well as the mass and viscosity of any fluid contained within the tube.

Some damping due to the viscous nature of a fluidized bed appears likely.

The frequency of vibration seems likely to be similar to the natural frequency of the tube (1). When the bubbles pass a tube with frequency close to the natural frequency of the tube, it is expected that the tube should vibrate with its largest amplitude; in other words, resonance would occur and the possibility for tube failure would be at a maximum. In practice, there are both stochastic and deterministic elements to the frequency of bubble passage (30) so that bursts of bubbles with different frequencies will occur in freely fluidized beds and design of tubes for fluidized beds should therefore take account of the worst (i.e., resonant) case.

4.2 Suggested Future Work

The following suggestions are made for related future work:

(1) At higher superficial gas velocities, because of "splashing effect" of particles, it was difficult and time-consuming to measure the height of the immersed part of floating objects. In order to take the data more easily, some means of blowing the particles away without creating any vertical force on the object should be devised.

(2) It would be interesting to know the time taken for the object to move back up after being pushed down below the surface of the fluidized bed. Some recent measurements of this type have been reported by Nienow et al (20).

(3) Under what conditions should a heavy object at the bottom of a fluidized bed begin to circulate like a fluidized particle in the bed. Confirmation of the three or four classes of objects proposed in Section 4.1.1 above would be welcome.

(4) For small particles where the superficial velocity corresponding to minimum bubbling is significantly larger than U_{mf} , it would be interesting to determine whether the buoyancy force is still governed by $\rho_p(1 - \epsilon_{mf})$ or whether the bed expansion beyond U_{mf} is reflected in a reduced effective density.

(5) Evaluation of pressure forces on immersed tubes should be carried out for a series of interacting bubbles with known frequency.

(6) It would be interesting to know the pressure of a bubble applied on vertical and inclined tubes. For a vertical tube, it is also important to determine under what conditions a bubble would enclose the tube as it rises.

(7) Measurement of the local pressure due to passage of bubbles

for horizontal and inclined tubes or rods should also be made in a three-dimensional fluidized bed. In this case, however, it will be difficult to know whether bubbles rise on a vertical trajectory and whether the tubes split as they encounter the tube or rod.

NOMENCLATURE

A, cm^2	Bed cross-sectional area.
A_B, cm^2	Bubble area.
b, cm	Half-width of the bed.
c, cm	Half-length of the bubble.
C_D	Drag coefficient.
$d_p, \mu\text{m}$	Particle diameter.
D_o, cm	Critical tube size.
F_B, dyne	Buoyancy force.
F_D, dyne	Drag force.
F_G, dyne	Gravitational force.
F_t, dyne	Net vertical pressure force.
$g, \text{cm/sec}^2$	Gravitational acceleration.
H_o, cm	Characteristic height of the object.
L, cm	Tube length.
M, g	Mass of the object.
N	Number of experimental data.
n_i	Number of data set.
$p, \text{cm of water}$	Pressure at a distance h below a surface of a bed.
$p_g, \text{cm of water}$	Pressure at the bed surface.
r, cm	Radial polar coordinate.
R, cm	Tube radius.
R_B, cm	Bubble radius.

s	Dimensionless radial coordinate.
S, cm	Arc length of the sphere submerged in the bed.
S_o, cm^2	Maximum cross-sectional area of the object.
$U, \text{cm/sec}$	Superficial gas velocity.
$U_B, \text{cm/sec}$	Bubble rising velocity.
$U_{BS}, \text{cm/sec}$	Slug velocity.
$U_{BCD}, \text{cm/sec}$	Collins' bubble velocity from Davidson's theory.
$U_{BCM}, \text{cm/sec}$	Collins' bubble velocity from Murray's theory.
$U_{Bee}, \text{cm/sec}$	Bubble velocity in isolation.
$U_{mf}, \text{cm/sec}$	Minimum fluidization velocity.
V_F, cm^3	Volume of fluid displaced by the object.
θ_1, degree	Angular position.
$\rho_{eff}, \text{g/cm}^3$	Effective density of the particulate phase.
$\rho_f, \text{g/cm}^3$	Fluid density.
$\rho_o, \text{g/cm}^3$	Density of the object.
$\rho_p, \text{g/cm}^3$	Particle density.
σ	Standard deviation.

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