COMPUTER SIMULATION OF HYDRODYNAMIC BEHAVIOR OF AGGREGATIVE FLUIDIZED BEDS

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Abstract Hydrodynamic behavior of aggregative fluidized beds has been studied and a model proposed for the prediction of different characterictics of fluidized beds. According to this model, a computer program is prepared and the hydrodynamic behavior of some industrial units has been simulated.

چکیده رفتار هیدرودینامیکی بسترهای سیالی نامتجانس موردمطالعه قرار گرفته و براساس این مطالعات یک مدل جهت پیش‌بینی خصوصیات مختلف این بسترها پیشنهاد گردیده است. با استفاده از مدل فوق یک برنامه کامپیوتری جهت بررسی رفتار هیدرودینامیکی بسترهای سیالی نامتجانس تهیه شده و چند واحد صنعتی توسط این برنامه شبیه‌سازی گردیده است.

INTRODUCTION

The first step in analyzing any physical or chemical process taking place in gaseous fluidized beds, is to study the hyrodynamic behavior of the system. At gas velocities above the minimum fluidization velocity, the gas in excess of the amount necessary to bring the bed to the state of minimum fluidization will appear in the form of bubbles in the bed. These bubbles are continuously formed above the distributor and rise up in the bed. During their passage through the bed, because of their coalescence with adjacent rising bubbles, the bubbles are in continous growth, and finally they appear as slugs with diameters approximately equal to that of the bed. The presence of bubbles and slugs, gives two different phases to be considered in the bed: 1) The continuous phase which consists of the solid particles and the gas perculating through them, and 2). The dispersed phase consisting of the gas passing through the bed in the form of bubbles and slugs. Figure 1 presents a schematic diagram of an aggregative fluidized bed. It should be noted that the appearance of slugs in these beds will only be possible if the proper conditions exist.

The presence of two different phases creates complications in the study of the flow pattern of the gas and solids. During the rise through the bed, there is a continuous exchange of gas

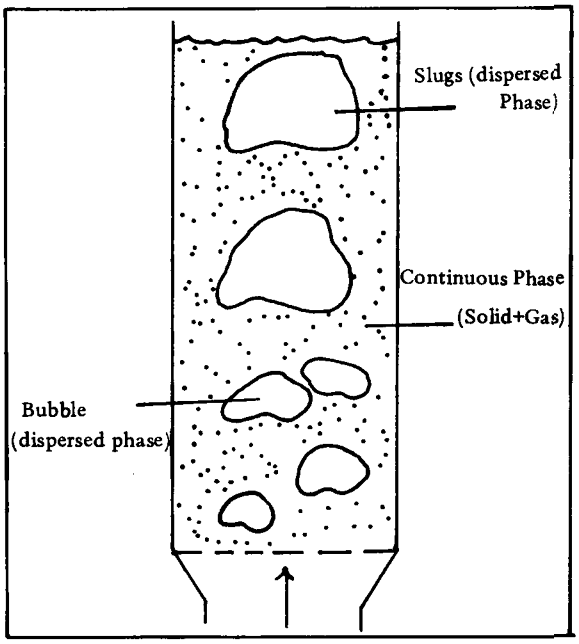


Figure 1. Aggregative Fluidized Bed

between the two phases and some of the solids may be entrained in the wake produced behind the bubbles. Also some may circulate in a thin region around the bubbles and slugs as a cloud. In this paper a tool for computer simulation of the hydrodynamic behavior of the preceeding model is presented.

THEORY

Bubbles and slugs have entirely different behaviorial patterns in fluidized beds. The size and velocity of a bubble is continuously changing during its rise until it forms a slug. Once the slug is formed it ascends with a constant diameter and velocity. So in studying the hydrodynamic behavior of an aggregative fluidized bed, bubbles and slugs must be treated separately.

1. BUBBLES

Hyrodynamic behavior of bubbles in fluidized beds has been studied by several investigators. The following formulas are descriptive of bubble behavior.

1. Bubble Diameter

The variation of bubble diameter as a function of its height in the bed has been studied by Calderbank [1], Whitehead [2], and Kobayashi [3]. However, the best results are predicted by Kobayahi's formula which follows.

$$D_b = 1.4\,\rho_p\, d_p\,(u/u_{mf})\,h + D_o \qquad (1)$$

where: $D_o = (6G/\pi)^{0.4}/g^{0.2}$, $G = \dfrac{u - u_{mf}}{n_o}$

and
$$u_{mf} = \frac{\mu}{d_p\,\rho_g}\left[(33.7)^2 + 0.408\,\frac{d_p^3\,\rho_g(\rho_p - \rho_g)g}{\mu^2}\right] - 33.7$$

2. Bubble Velocity

The rising velocity of a bubble relative to solids in the continuous phase is given by Davidson and Harrison [4] as:

$$u_b = 0.711\,(gD_b)^{0.5} \qquad (2)$$

While its absolute velocity is given by:

$$\acute{u}_b = (u - u_{mf}) + u_b \qquad (3)$$

3. Gas Exchange Rate Between Phases

The rate of gas exchange between the bubble and the continuous phase has been studied by Zenz [5], Kunii and Lenvenspiel [6], Kobayashi [7], and also Davidson and Harrison [4], whose expression is used in this paper as:

$$Q = 3/4\,\pi\,u_{mf}\,D_b^2 + 0.975\,D_G^{1/2}\,D_b^{-1/4}\,g^{1/4} \qquad 4)$$

4. Expanded Bed Height

At velocities above the minimum fluidization velocity, the fluidized bed expands and its height increases. The expanded bed height for bubbling beds could be calculated by assuming an effective bubble diameter corresponding to the diameter of the bubble at the mean minimum fluidization height of the bed.

$$L_b = L_{mf} + L_{mf}\left[(u - u_{mf})/0.711\,(g\,D_b)^{1/2}\right] \qquad (5)$$

where $D_b = 1.4\,\rho_p\,d_p\,(u/u_{mf})\,L_{mf}/2 + D_o$

5. Bed Porosity

The overall porosity of the bed in the bubbling region is expressed by Kunii and Levenspiel [8] as:

$$\epsilon = 1 - L_{mf}/L_b\,(1 - \epsilon_{mf}) \qquad (6)$$

while the porosity of the continuous phase is assumed to be that of minimum fluidization state (ϵ_{mf}).

6. Bubble Shape and Volume

Bubbles are assumed to be spherical therefore their volume is taken as the volume of a sphere of diameter D_b. The radius of the cloud of circulating gas around the bubble is give by Davidson and Harrison [4] as:

$$r_c = r_b\ [(\alpha_b + 2)/(\alpha_b - 1)]^{1/3} \qquad (7)$$

where $\alpha_b = u_b\, \epsilon_{mf} / u_{mf}$

It should be noted that a cloud is formed only by the bubbles for which $\alpha_b > 1$.

2. SLUGS

The majority of the studies on hydrodynamic behavior of slugging beds has been done by Stewart [10]. The results of these studies are given in the following sections:

1. Slug-Rise Velocity

The rising velocity of a slug relative to the solids of the continuous phase is constant through the bed height and is controlled by the bed walls. This velocity is given by Lazer [9] as:

$$u_s = 0.35\, (g D)^{1/2} \qquad (8)$$

Based on this relative velocity the absolute velocity of a slug is given as:

$$u_s' = (u - u_{mf}) + u_s \qquad (9)$$

2. Expanded Bed Height

The height of the slugging bed in the expanded bed is in continuous variation between a maximum and minimum value. The maximum expanded bed height which is involved in the analysis of the slugging bed is given by Stewart [10] as:

$$L_{max} = L_{mf} + L_{mf}\, (u - u_{mf} / u_s) \qquad (10)$$

3. Length of Slug

The length of a complete slug in a slugging bed is calculated by solving the following Equation [10].

$$\frac{L_s}{} \quad 0.495\, (\frac{L_s}{D})^{1/2} [1 - \frac{u - u_{mf}}{u_s} +$$

$$0.061 - 1.939\, (\frac{u - u_{mf}}{u_s}) = 0 \qquad (11)$$

4. Gas Exchange Rate Between Phases

The gas in the continuous phase is beleived to enter the slug at its base and exit from its top. Since a slug nearly covers all the bed diameter, the rate of exchange of gas between phases could be calculated as [11]:

$$Q_s = \pi/4 \cdot (D^2\, u_{mf}) \qquad (12)$$

5. Slug Volume

The volume of a slug is given by Nicklin [12]:

$$V_s = \pi D^3/4\ [L_s/D - 0.495\, (L_s/D)^{1/2} + .061] \qquad (13)$$

THE MODEL

Several mathematical models for simulation of the hydrodynamics of aggregative fluidized beds have been presented, among which are models proposed by Palancz [14], Zenz [15], Vander Borg and Beestcheerde [16], and Viswanathan [17]. In the present model, the expanded bed height is divided into successive compartments and the characteristics of bubbles or slugs in each compartment are simulated separately (Figure 2). The models for bubbling and slugging regions are discussed below.

1. Bubbling Region

In simulating the bubbling region, first the expanded bed height, assuming only bubbles to be present in the bed, is calculated using

Equation 5, and then overall porosity of this region is found using Equation 6. In a procedure similar to that followed by Kato et al. [13], the bubbling region is divided into several compartments where the height of each compartment is taken as the average size of the bubbles present at its ends. The diameter of the bubbles in each compartment will be:

$$D_{bn} = 2D_o \,(2 + m)^{n-1} / (2 - m)^n$$

where n is the number of the compartment counted from the distributor and $m = 1.4\rho_p d_p \,(u/u_{mf})$. The height of each bubble above the distributor is calculated as:

$$h_n = h_{n-1} + D_{bn}$$

After evaluation of the bubble diameter at any elevation, the velocity of the bubble and the rate of gas exchange between the phases in that elevation can be readily calculated using Equations 2 and 4 respectively.

The number of bubbles in a compartment at a definite elevation is calculated using Equation 16:

$$N_n = 6S\,(\epsilon - \epsilon_{mf}) \,/\, \pi (D_b)^2 \,(1 - \epsilon_{mf})$$

The total volume of bubbles in a compartment, and that of the clouds if present, is calculated using Equations 14 and 7 respectively:

$$V_{bn} = N_n \,\pi\, (D_{bn})^3 / 6 \qquad (17)$$

$$V_{cn} = N_n \,\pi\, (D_{bn})^3 / 6 \,.\, (3u_{mf}/\epsilon_{mf}) \,/\, (u_b - u_{mf} / \epsilon_{mf})$$

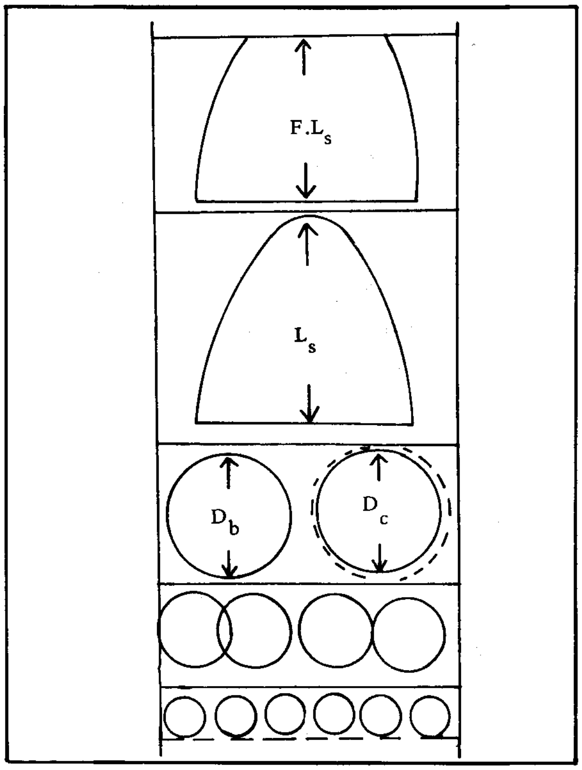


Figure 2: Hydrodynamic Model of an Aggregative Bed.

Table 5-1. Simulation Results of a Pilot Scale Dehumidification Unit

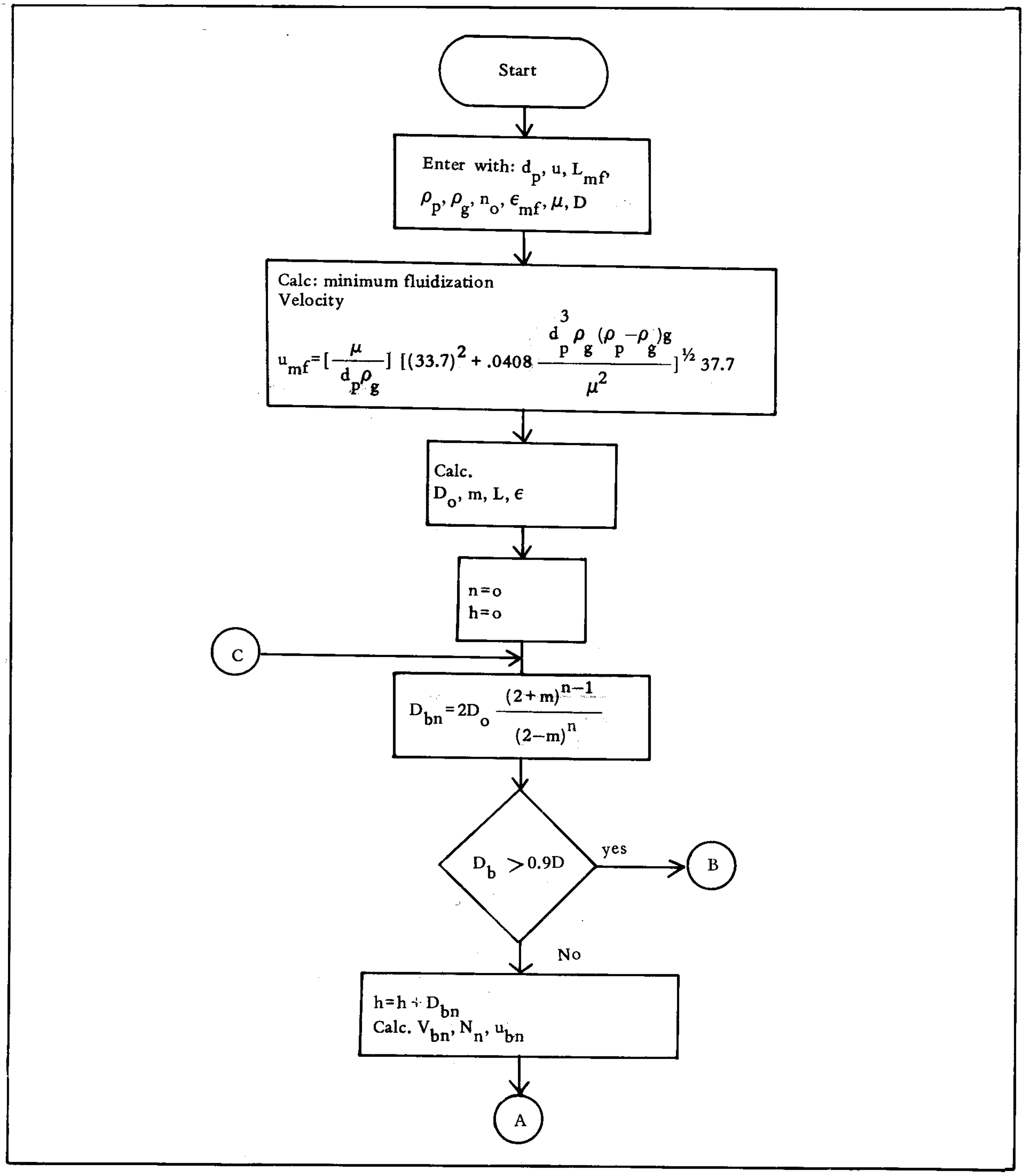
h(cm)	D_b(cm)	u_b(cm/s)	N_n	V_{bn} (cm^3)	Q_{bub}· (cm^3/s)	L_s(cm)	u_s(cm/s)	Q_{slug} (cm^3/s)
2.106326	2.106326	32.30319	15.6202	24.32833	15027.27	–	–	–
6.909775	4.803449	48.78194	3.003528	55.48046	14926.75	–	–	–
23.4545	–	–	–	–	–	7.101395	34.64823	363.4826
39.99923	–	–	–	–	–	7.101395	34.64823	363.4826
56.54396	–	–	–	–	–	7.101395	34.64823	363.4826
63.64535	–	–	–	–	–	7.101395	34.64823	363.4826

Operating Conditions: Temp. = 30°C, Press. = 1 atm, Gas Visco. = 0.0002 gr/cm.s, dp = 0.3 cm ρ_p = 1.1 Kg/lit, No. of Perforation = 2 cm^{-2} u_{mf} = 88.77 cm/s, u = 150 cm/s, D = 10 cm

2. Slugging Region

When the bubble diameter calculated in a compartment approaches nine-tenths of the bed diameter [11], the slugging region is believed to be initiated. Here the maximum expanded bed height for slugging beds is calculated using Equation 10. Then the size of a slug, which is assumed to be constant throughout the bed, is determined by solving Equation 11. The maximum expanded bed height is divided into successive compartments of height L_s. If the maximum bed height is not an

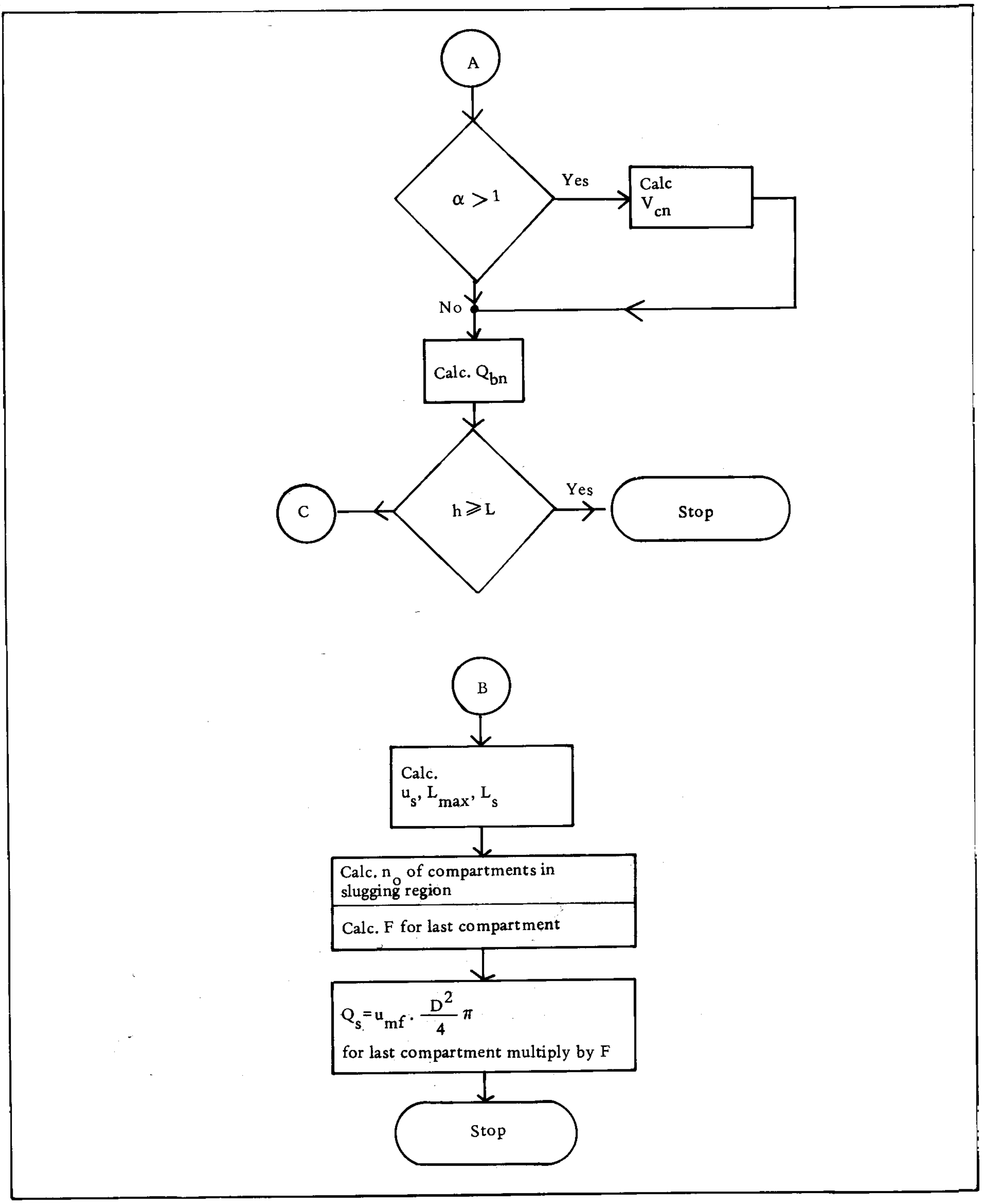
Figure 3: Flowchart of computer program for simulation of hydrodynamic behavior of fluidized beds.



integer multiple of the slug length, the height of the last compartment in the slugging region is taken to be a fraction of the slug length (F. L_s) where F is a fraction of one. Parameters introduced in describing slug behavior are calculated and taken to be constant throughout the slugging region.

COMPUTER PROGRAM

A computer program for simulation of the



hydrodynamic behavior of aggregative fluidized beds based on the proposed model is prepared. In this program, first the bubbling region of the bed is simulated. If the diameter of the bubbles reaches the slug limit, the simulation of the slugging region will be carried out. Otherwise, the bed is treated as a bubbling bed. A flowchart of the program is presented on the preceeding page.

Table 5-2. Simulation Results of a Ore Roasting Unit

h(cm)	D_b(cm)	u_b(cm/s)	N_b	V_{bn}(cm^3)	Q(cm^3/s)
1.432107	1.432107	26.63608	52186.99	25546.84	1.164003E + 07
3.887872	2.455765	34.87998	17747.59	43807.52	1.152425E + 07
8.098998	4.211127	45.67534	6035.545	235879.2	1.142307E + 07
15.3202	7.221206	59.81189	2052.549	404483.8	1.133465E + 07
27.70307	12.38287	78.32373	698.0245	693605.6	1.125739E + 07
48.93711	21.23404	102.565	237.382	1189389	1.118987E + 07
58.34907	36.41196	134.3089	80.72815	2039555	1.113087E + 07
147.788	62.43895	175.8776	64.0904	8164660	2.586448E + 07

Operating Conditions: Temp. =514.27°C, Press. = 1 atm, Gas Visco. = 0.00025 gr/cm.s, dp = 0.1 cm ρ_p = 2 kg/lit, No. of Perforation = 2 cm^{-2}, u_{mf} = 42.53 cm/s, u= 80 cm/s, D = 560 cm

Table 5-3. Simulation Results of Fluid-Bed Catalytic Cracking Unit.

h(cm)	D_b(cm)	u_b(cm/s)	N_n	V_{bn} (cm^3)	$Q_{bub.}$ (cm^3/s)	L_s(cm)	u_s(cm/s)	Q_{slug} (cm^3)
0.97	0.97	22	12114	5919	114171	—	—	—
3.1	2.1	32	2583	12818	94989	—	—	—
7.7	4.6	47	550	27261	79176	—	—	—
17.	9.9	70	117	60120	66141	—	—	—
39	21	103	25	130198	53596	—	—	—
85	46	151	5	281962	46539	—	—	—
186	100	223	2	610627	39237			
404	218	328	1	1322393	—	—	—	—
484	—	—	—	—	— —	59.4	268	7056541
782	—	—	—	—	—	59.4	268	7056541
1080	—	—	—	—	—	59.4	268	7056541
1140	—	—	—	—	—	—	—	—

Operating Conditions: Temp=500°C, Press=1 atm, Gas Visco=0.00025 gr/cm.s, dp=0.008 cm, ρ_p=1.2 kg/lit., No. of Perforation=2cm^{-2}, u_{mf}=0.182 cm/s, u=10cm/s, D=600cm.

RESULTS

The hydrodynamic behaviors of a fluidized catalytic unit, a fluidized bed ore roasting unit, and a pilot scale fluidized bed of silica-gel particles (used for air dehumidification) were simulated using the proposed model. In each simulation, bubbles and slug size and velocity, and the rate of gas exchange between phases, at different elevations in the bed were calculated. The results of the simulations are given in Tables 5-1, 5-2 and 5-3.

NOTATIONS

1- Alphabetic Symbols:

D_G Gas Diffusivity (cm^3/s)
D_{bn} = Diameter of bubbles in a compartment (cm)
D_b = Average bubble diameter (cm)
D = Bed diameter (cm)
D_b = Bubble diameter (cm)
D_o = Bubble diameter at the entrance to the bed (cm)
d_p = Particle diameter (cm)
F = Degree of completion of a slug (fraction)
g = Acceleration of gravity (cm^2/s)
h = Elevation in the bed measured from the distributer (cm)
L_s = Length of a slug (cm)
L_b = Expanded height of a bubbling bed (cm)
L_{mf} = Bed height at minimum fluidization (cm)
L_{max} = Maximum expanded bed height in a slugging bed (cm)
N_n = Number of bubbles in a compartment
n_o = Number of perforation per unit area of distribution
Q = Gas exchange rate between phases in bubbling bed (cm^3/s)
Q_s = Gas exchange rate between phases in slugging bed (cm^3/s)
r_b = Bubble radius (cm)
r_c = Cloud radius (cm)
S = Cross sectional area of a cylindrical bed (cm^2)
u = Superfical gas velocity (cm/s)
u_b = Bubble rise velocity relative to solid particles (cm/s)
u'_b = Absolute bubble rise velocity (cm/s)
u_{mf} = Superficial gas velocity at minimum fluidization (cm/s)
u_s = Slug rise velocity relative to solid particles (cm/s)
u'_s = Absolute slug rise velocity (cm/s)
V_{cn} = Volume of clouds in a compartment (cm^3)
$_{bn}$ = Total volume of bubbles in a compartment (cm)
V_s = Volume of slug (cm^3)

2- Greek Symbols:

ρ_p = Particle density (gr/cm^3)
ρ_g = Gas density (gr/cm^3)
ϵ_{mf} = Bed porosity at minimum fluidization
ϵ = Bed porosity
μ = Gas viscosity (gr/cm, s)

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