Existence of Turbulent Regime in Gas-Solid Fluidization

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Circulating fluidized beds (CFB) have been applied extensively in industry for catalytic cracking of oil, coal combustion and gasification, alumina calcination and others (for example, Reh, 1986; Contractor and Chaouki, 1990). A CFB can be operated at different flow regimes from turbulent and fast fluidization to dilute transport. This work examines the nature of the existence of the turbulent regime and its transition, and provides a unified interpretation of this transition based on existing definitions of the turbulent and transport regimes and available experimental data covering a wide range of operating conditions.

Transport Velocity, U_{tr}

In a CFB, by varying the solids circulation rate at a given gas velocity, a critical solids circulating rate may exist where a sharp change in the solids holdup gradient takes place at the lower part of the bed. As the gas velocity increases beyond a certain point, such a sharp change in the solids holdup gradient disappears. The gas velocity at this critical point is known as the transport velocity U_{tr} (Yerushalmi and Cankurt, 1979), which earmarks the onset of fast fluidization regime (for example, Horio, 1990). In addition to pressure drop measurement, the transport velocity can be determined by other methods such as saturation carrying capacity (Chen et al., 1980; Li and Kwauk, 1980), bed expansion (Avidan and Yerushalmi, 1982), elutriability of particles from a fluidized bed (Le Palud and Zenz, 1989), the emptying time decay of bed particles (Han et al., 1985; Perales et al., 1990), and the pressure fluctuation (Leu et al., 1990; Yang et al., 1990). Table 1 summarizes numerous experimental studies reported in the literature concerning U_{tr}. The methods used in determining U_{tr} are also indicated. It is seen in the table that the particles employed include those of Geldart's groups A, B and D with particle diameter and density varying from 33 to 5,000 μm and from 660 to 4,510 kg/m^3, respectively. The column diameters vary from 5 to 30 cm. The values of U_{tr} in terms of Re_{tr} defined by $(\rho_g U_{tr} d_p/\mu_g)$ vary from 2.42 to 2,890.

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Onset Velocity for Turbulent Regime, U_k

Based on the variation in the variance of the pressure fluctuation with the gas velocity, it is typical that the gas velocity corresponding to the peak of the variation, U_c, defines the onset of the transition to the turbulent regime, while that corresponding to the point where the variation levels off, U_k, defines the onset of the turbulent regime. With these definitions, the existence of the turbulent regime has been reported in numerous studies (for example, Lanneau, 1960; Kehoe and Davidson, 1970; Massimilla, 1973; Thiel and Potter, 1977; Canada et al., 1978; Yerushalmi and Cankurt, 1979). Table 2 summarizes available experimental studies reported in the literature concerning U_k. In addition to the pressure fluctuation method, U_k was also determined by methods including capacitance probe, X-ray photography, and visualization.

Among various studies, Leu et al. (1990) found that for sand particles with increasing gas velocity the variance of measured pressure fluctuation at the lower section of the riser levels off at U_k, maintains a constant value, and decreases again after passing the transport velocity U_{tr}. Perales et al. (1990) found that the values of U_k and U_{tr} in a CFB for glass beads and FCC particles employed were nearly the same and questioned the existence of a turbulent regime. A similar observation was reported earlier by Yang (1982), who based on the pressure fluctuation data of Li and Kwauk (1980), argued that U_k in that study may well represent the termination instead of the onset of the turbulent regime.

Correlations

Based on the available data in the literature summarized in Tables 1 and 2, correlations for Re_{tr} and Re_k in terms of Ar, where Ar is the Archimedes number are presented as shown in Figure 1. For comparison, Geldart's demarcations of groups A, B and D particles in terms of Ar, which is applicable for particles with $(\rho_s - \rho_g)/\rho_g$ ranging from about 1,000 to 2,000 (Grace, 1986), is also shown in the figure along with the variation of the Reynolds number based on single-particle terminal velocity, Re_t, with Ar. The figure shows that both Re_{tr} and Re_k increase with an increase in Ar. Furthermore, at Ar less than 125, for a given Ar, Re_k is lower than Re_{tr}. At Ar larger

Table 1. Reported data on U_{tr}

Reference	solids	d_p (μm)	D_t (mm)	ρ_s (kg/m^3)	U_{tr} (m/s)	Re_{tr}	Exp. Method
Yerushalmi and Cankurt (1979)	FCC	49	152	1,070	1.37	4.57	PUG
	HEF-20	49	152	1,450	2.1	5.9	PUG
	Alumina	103	152	2,460	3.85	6.9	PUG
Chen et al. (1980)	FCC	58	90	1,780	1.25	4.83	ϵUG
	Alumina	54	90	3,160	2.0	7.2	ϵUG
	Alumina	81	90	3,090	2.6	14.0	ϵUG
	Iron ore	56	90	3,050	2.0	7.47	ϵUG
	Iron ore	105	90	4,510	4.0	28.0	ϵUG
Li & Kwauk (1980)	Alumina	54	90	3,160	2.45	8.82	ϵUG
Avidan & Yerushalmi (1982)	Catalyst	33	152	1,670	1.10	2.42	BE
Lee & Kim (1982)	Cement raw meal	23.6	78	2,500	1.8	2.83	TDU
Shin et al. (1984)	Coal	205	78	1,720	1.58	21.6	TDU
	Coal	395	78	1,720	2.28	60.0	TDU
Han et al. (1985)	Coal	730	78	1,400	1.78	86.6	TDU
	Coal	1,030	78	1,400	2.09	143.5	TDU
Kwauk et al. (1986)	FCC	58	300	1,780	1.85	7.2	ϵUG
Le Palud & Zenz (1989)	FCC	35-90	102	1,250	0.61-0.91	--	EU
	GB	65-104	102	2,404	0.88-2.13	--	EU
Li et al. (1988)	FCC	54	90	930	2.50	9.0	ϵUG
Horio et al. (1989)	FCC	60	50	1,000	0.92	3.7	PUG
Leu et al. (1990)	sand	~90	108	~2,600	~2.27	13.7	PF
Bi et al. (1991)	PE	~325	102	660	2.25	48.7	PUG
Yang et al. (1990)	FCC	67	224	1,700	1.5	6.7	PF
Perales et al. (1990)	Sand	120-1,200	92	2,650	--	18-350	TDU
	FCC	80	92	1,715	1.6	9.0	TDU
Jiang & Fan (1991)	PE	3,400	102	1,010	4.6	1,037	PUG
	PE	4,500	102	920	5.02	1,498	PUG
	GB	2,160	102	2,500	6.99	1,001	PUG
	GB	5,000	102	2,500	8.65	2,890	PUG

PUG = diagram of pressure gradient vs. solids circulation rate at series of given gas velocities.
ϵUG = saturation carrying capacity based on the diagram of average voidage vs. gas velocity at fixed solids circulation rate.
TDU = time decay diagram of particles elutriation as a function of superficial gas velocity.
EU = elutriation vs. gas velocity.
PDF = pressure drop fluctuation.
PF = pressure fluctuation.
BE = bed expansion.
FCC = fluid cracking catalyst.
GB = glass beads.
PE = polyethylene.

than 125, however, Re_k is virtually identical to Re_{tr}. It is noted that Ar of 125 corresponds to the demarcation between group A and B particles. The correlations for the data in Figure 1 can be expressed by:

$$Re_{tr} = 2.28 Ar^{0.419} \tag{1}$$

$$Re_k = 0.601 Ar^{0.695}, \quad \text{for } Ar \leq 125 \tag{2a}$$

$$Re_k = 2.28 Ar^{0.419}, \quad \text{for } Ar \geq 125 \tag{2b}$$

The correlation coefficients for Eqs. 1 and 2b, and Eq. 2a are 0.986 and 0.790, respectively.

Discussion

The well-correlated equations given above have an important implication in that the turbulent regime in effect exists only for $Ar < 125$, but not for $Ar > 125$. Specifically, the turbulent regime is in existence only for group A particles but not for group B and D particles. Physically, for group A particles, the fully developed turbulent regime bounded by U_{tr} and U_k is established; in this regime, bubble breakage dominates over bubble coalescence, and particle entrainment is increased through bubble bursting as the gas velocity increases beyond the bubbling regime. For group A particles, Figure 1 shows that the data for transition velocity U_k or Re_k are rather scattered and are in general higher than Re_t due to particle clus-

Table 2. Reported experimental data on U_k

Reference	Solids	d_p (μm)	D_t (mm)	ρ_s (kg/m^3)	U_k (m/s)	Re_k	Exp. method
Kehoe & Davidson (1970)	Catalyst A	22	100	1,100	0.11	0.16	XP
	Ballotini	22	100	2,200	0.35	0.51	XP
	Ballotini	22	50	2,200	0.40	0.59	CP
	Ballotini	22	620×6	2,200	0.35	0.51	CP
	Catalyst B	26	100	1,100	0.18	0.31	CP, XP
	Catalyst B	26	100	1,100	0.32	0.30	CP
	Catalyst B	26	620×6	1,100	0.17	0.56	CP
	Catalyst C	55	100	1,100	0.44	1.61	XP
	Catalyst C	55	50	1,100	0.5	1.83	CP
	Catalyst C	55	100	1,100	0.50	1.83	CP
Massimila (1973)	Catalyst	50	156	1,000	0.35	1.18	CP
Carotenuto et al. (1974) & Crescitelli et al. (1978)	Catalyst	60	152	940	0.2	0.80	PF, CP
	Alumina	95	152	1,550	1.0	6.33	PF, CP
	Ludox	60	152	1,400	0.33	1.32	PF, CP
Theil & Potter (1977)	FCC	60	51	930	0.41	1.64	V
	FCC	60	102	930	0.22	0.88	V
	FCC	60	218	930	0.0225	0.09	V
Canada et al. (1978)	GB	650	300×300	2,480	2.56	112.00	PF, CP
	GB	2,600	300×300	2,920	4.19	733.60	PF, CP
Yerushalmi & Cankurt (1979)	Dicalite	33	152	1,670	1.07	2.35	PDF
	FCC	49	152	1,070	0.61	1.99	PDF
	HFZ-20	49	152	1,450	1.37	4.48	PDF
	HFZ-20	49	510×50	1,450	1.07	3.50	PF
	Alumina	103	152	2,460	2.74	18.81	PDF
	Alumina	103	510×50	2,460	2.55	17.51	PF
	Sand	268	152	2,650	5.50	98.27	PDF
Satija & Fan (1985)	GB	1,000	102	2,767	3.87	260.60	PF
	Alumina	2,320	102	3,537	5.34	834.60	PF
	Alumina	5,500	102	3,537	7.66	2,840.00	PF
	Alumina	6,960	102	3,537	8.49	3,984.10	PF
Rhodes & Geldart (1986)	Vermiculite	223	152	327	1.98	30.70	PDF
	Alumina	42	152	1,015	1.38	4.03	PDF
	CBZ-1	38	152	1,308	1.44	3.80	PDF
	E-cat	40	152	1,618	1.45	4.03	PDF
	FRF-5	66	152	2,335	2.52	11.55	PDF
	Sand	69	152	2,665	2.80	13.42	PDF
Mori et al. (1988	FCC	56	50	729	1.26	4.7	PF
	Catalyst	78	50	2,400	2.1	10.9	PF
	Catalyst	134	50	2,400	2.3	20.6	PF
Son et al. (1988)	Sand	430	380	2,630	2.50	72.47	PF
Leu et al. (1990)	Sand	~90	108	2,600	1.67	10.1	PF
Perales et al. (1990)	Sand	120-1,200	92	2,650	--	20-270	PDF
	FCC	80	92	1,715	2.10	12.0	PDF
Jiang & Fan (1991)	PE	3,400	102	1,010	4.6	1,037	V
	PE	4,500	102	920	5.02	1,498	V
	GB	2,000	102	2,500	6.99	1,001	V
	GB	5,000	102	2,500	8.65	2,890	V

CP = capacitance probe.
XP = x-ray photography.
V = visual.
PF = pressure fluctuation.
PDF = pressure drop fluctuation.
FCC = fluid cracking catalyst.
GB = glass beads.

tering effect caused by interparticle forces of attraction. Measurement methods appear to have some effects. Visual observation, X-ray photography, or capacitance probe as employed , for example, by Kehoe and Davidson (1970) and Thiel and Potter (1977) yields data for Re_k significantly lower than those for Re_{tr}. On the other hand, the pressure fluctuation method yields data for Re_k close to Re_{tr}. Data scattering may also be due to the particle size distribution effect. In the studies of Mori et al. (1988) and Leu et al. (1990), the pressure fluctuation decreases with gas velocity after leveling off beyond

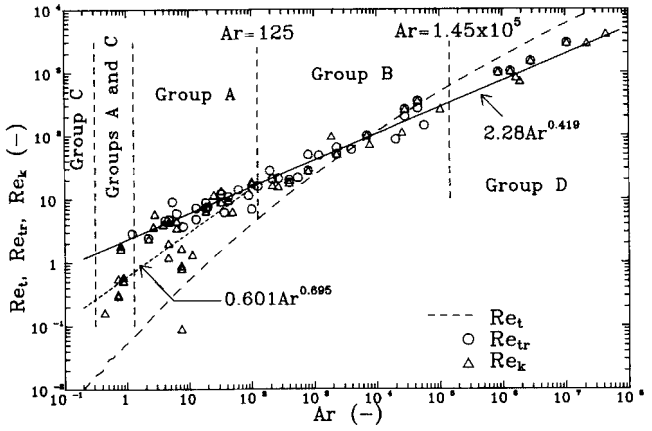

Figure 1. Variation of Re_t, Re_k and Re_{tr} with the Archimedes number.

the peak point. Leu et al. (1990) found that at the gas velocity exceeding this decreasing point, or U_{tr}, significant solids are carried away in the bed. Le Palud and Zenz (1989) also found that the data for U_{tr} of Yerushalmi and Cankurt (1979) could be predicted well by their correlation developed based on the monosized particle data, if the maximum particle size, instead of mean particle size, can be used for the correlation. This finding implies that the coarse component of the particle mixture plays a dominant role on U_{tr}. Thus, it is reasonable to state that the range of gas velocities for constant pressure fluctuation reported by Mori et al. (1988) and Leu et al. (1990) could be significantly smaller, or U_{tr} would be substantially closer to U_k, if monosize particles are used.

For the systems with group B particles, large gas bubbles or gas slugs are present. With increasing gas velocity, the formation frequency of solid slugs decreases (Mori et al., 1988) and eventually solids are entrained from the bed. Thus, the transition takes place directly from the bubbling/slugging regime to the fast fluidization regime bypassing the turbulent regime. Present correlations are consistent with the experimental results of Kehoe and Davidson (1970) in which the turbulent fluidization regime was obtained only in the systems using particles smaller than 70 μm, and of Carotenuto et al. (1974) in which the turbulent fluidization regime was attained in the system of 95-μm alumina particles, while for the system containing 270-μm alumina particles the turbulent regime was not attained.

For systems with group D particles, Jiang and Fan (1991) found that the regime transition phenomenon depends strongly on whether the operation is in solids-batch or solids-continuous mode. For the solids-batch mode operation, the solids slugs thin up with the increasing gas velocity and eventually at gas velocity U_k ($\approx U_{kb}$), slugs break down leading to the turbulent regime. As the gas velocity further increases approaching the single-particle terminal velocity, the bed voidage approaches unity and the particles begin to be in transport motion. For solids-continuous mode operation, there is no apparent difference in the flow structure in the slugging regime from the solids-batch mode operation. At a given solids circulation rate, as the gas velocity increases to U_k, the solids slugs disappear, and the bed undergoes transition to the turbulent regime. At this point, solid particles are in transport mode and thus the bed is in effect in the transport regime: U_k and U_{tr} are practically the same. Technically, it can be stated that the turbulent regime is bypassed. The transport velocity is consequently lower than the particle terminal velocity for group D particles for solids-continuous mode operation as shown in Figure 1.

In addition to the particle properties, column size also affects U_k for group A particles: U_k decreases with an increase in column diameter, as evidenced from the data of Kehoe and Davidson (1971), Thiel and Potter (1977), and Carotenuto et al. (1974), utilizing particles of similar properties: d_p = 55–60 μm, ρ_s = 930–1,100 kg/m^3 (see Table 2). The column size effect can be explained by the fact that for group A particles, the bubbling behavior depends on the stable bubble size that is inherently affected by the column size. An increase in column size at a given operating condition increases the bubble size, and hence the pressure fluctuation and extent of turbulence, aiding the flow transition to the turbulent regime. Considering the column size effect, the data for Eq. 2a can be recorrelated as:

$$Re_k = 16.31 Ar^{0.136} (U_t/\sqrt{gD_t})^{0.941}, \quad \text{for } Ar \le 125 \qquad (3)$$

The correlation coefficient for Eq. 3 is 0.810. Thus, for group A particles, the transition velocity U_k is related strongly to the bubble coalescence and breakup, while the transport velocity U_{tr} varies significantly with the particle elutriability. Indeed, experimental data on larger beds are needed to substantiate the column size effect precisely in the correlation for U_k for group A particles. The type of solids recycling system may also have an effect on U_k and U_{tr}. Rhodes and Geldart (1986) classified the system into five types and reported that the fluidization phenomena observed in different systems are different. In their type II system (see Figure 3 of their article), it was found U_k is a function of particle properties only, while U_k in their type V system was found to be affected also by solids circulating rate. Leu et al. (1990) reported that U_k can be obtained for type II system, but not type V system. The method for determining U_{tr} proposed by Yerushalmi and Cankurt (1979) was also put in question by Schnitzlein and Weinstein (1988), whose experiments showed that U_{tr} was unattainable by this method. Clearly, Ar is not the unique variable for Re_{tr} or Re_k for group A particles.

For group B and D particles, U_k or U_{tr} does not appreciably vary with column size apparently due to the insignificant column size effect on particle entrainment characteristics induced by large bubbles/slugs and hence the transition behavior. This is evidenced by a small exponent of D_t in the correlation when the data for Eq. 1 or 2b are recorrelated as:

$$Re_k = 2.274 Ar^{0.419} (U_t/\sqrt{gD_t})^{0.0015}, \quad \text{for } Ar \ge 125 \qquad (4)$$

The correlation coefficient for Eq. 4 is 0.986.

Finally, the experimental data for U_k and U_{tr} for high-pressure and high-temperature operating conditions are needed to generalize the correlation equations proposed here.

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Notation

Ar = $d_p^3 \rho_g g (\rho_s - \rho_g)/\mu_g^2$
d_p = mean particle diameter, μm
D_t = bed diameter, mm
g = acceleration due to gravity, m/s^2
Re_k = $(\rho_g U_k d_p)/\mu_g$
Re_t = $(\rho_g U_t d_p)/\mu_g$
Re_{tr} = $(\rho_g U_{tr} d_p)/\mu_g$
U_c = onset velocity of the transition to turbulent regime, m/s
U_k = onset velocity of turbulent regime, m/s
U_{kb} = onset velocity of the transition to turbulent regime under solids-batch operating conditions, m/s
U_t = particle terminal velocity, m/s
U_{tr} = transport velocity, m/s

Greek Letters

ρ_g = density of the gas, kg/m^3
ρ_s = density of the particles, kg/m^3
μ_g = viscosity of the gas, N/m^2

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