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TYPES OF CHOKING IN VERTICAL PNEUMATIC SYSTEMS

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Abstract—Choking is examined in terms of its definitions. Three choking initiation mechanisms are identified: type A (accumulative) choking occurs when solids start to accumulate at the bottom of the conveyor as the saturation gas carrying capacity is reached; type B (blower-/standpipe-induced) choking results from instabilities due to gas blower–conveyor or solids feeder–conveyor interactions where there is insufficient pressure or too limited solids feed capacity to provide the needed solids flow; and type C (classical) choking corresponds to a transition to severe slugging. Approaches for predicting the onset of each of these type of choking are recommended. Implications for regime transitions in fast fluidization are also identified.

Key Words: choking, instability, fast fluidization, dilute-phase pneumatic transport, dense-phase pneumatic transport

INTRODUCTION

When gas flows vertically upward through a bed of solid particles, the batch operation mode with a distinct bed surface is replaced by pneumatic transport when the gas velocity exceeds the transport velocity U_{tr} (Yerushalmi *et al.* 1978; Schnitzlein & Weinstein 1988). In the opposite direction, stable operation of conventional pneumatic transport ceases when the gas velocity is reduced below the choking velocity (Leung 1980; Reddy Karry & Knowlton 1991; Bi & Fan 1991). In recent years, a fast fluidization regime has been proposed somewhere between the lower velocity fluidization regimes (bubbling, slugging and turbulent fluidization) and the pneumatic transport regime. Such a fast fluidization regime, however, is still not well-defined, in large measure due to poor understanding of choking phenomena (Grace 1986; Bi & Fan 1991). A proper understanding of choking would aid in understanding the mechanisms which govern hydrodynamic regime transitions and in bridging the gap between conventional fluidization/dense-phase transport and pneumatic transport.

This paper seeks to clarify the use of the term choking as it has been employed in different manners in the literature and to offer suggestions regarding how to predict choking for different equipment and gas–solids systems. Implications for regime transitions in circulating fluidized beds (CFBs) are then considered in the light of the discussion of different modes of choking.

INITIATION OF CHOKING

Choking Definitions

The term "choking" has been generally used to describe a phenomenon which occurs when there is an abrupt change in the behaviour of a gas–solids conveying system. A number of definitions and criteria have been developed to describe and predict choking conditions. For a tall vertical riser in which solid particles are being conveyed at a given rate and the gas velocity is gradually reduced, Zenz & Othmer (1960) defined choking as the point at which slugging occurred to such an extent that extremely unsteady flow conditions ensued. In a similar approach, Yousfi & Gau (1974) defined choking as occurring when solids plugs extend over the entire pipe cross section. The choking point, therefore, has been characterized by the formation of slugs/plugs and severe

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instability. Such an unsteady transition, which we will refer to as "classical choking" or type C choking, was determined by Zenz (1949), Lewis *et al.* (1949), Ormiston (1969), Drahos *et al.* (1988), Mok *et al.* (1989) and Bi *et al.* (1991).

Based on such a definition, choking has been found to depend on the properties of both gas and solid particles, as well as on the size and geometry of the column which contains the flow system (Zenz 1949; Yousfi & Gau 1974). For large particles, choking was observed to result in slugging; for smaller particles slugging does not come into play. To clarify a system as slugging or non-slugging, criteria have been proposed based on instability analysis of uniform suspension flow (Yousfi & Gau 1974), stability of slugs (Yang 1976) and the propagation of continuity waves (Smith 1978). For large units with small particles, when the maximum stable bubble size is much smaller than the column diameter, slugging is not encountered.

The second type of choking, which has been called "premature choking" (Reddy Karri & Knowlton 1991), results from equipment (blower or standpipe) limitations. No slugging appears, but the system becomes inoperable. This unstable condition may be due to the inability of the blower to provide sufficient pressure head to support all of the particles in suspension (Zenz & Othmer 1960) plus the head losses through the gas distributor, riser exit, cyclone etc. With blowers characterized by reducing volumetric delivery at increasing delivery pressure, Doig & Roper (1963) and Leung *et al.* (1971) analyzed such an instability process as shown in figure 1. The solid lines represent the pressure head at the bottom of the conveyor vs superficial gas velocity, U_G, while the dashed lines are characteristics of the blower. For a fixed solids flow rate, there are two possible operating points, A and B, with point B inherently unstable. A small reduction in the gas flow rate at B would result in an increase in the pressure drop, resulting in a further decrease in the gas flow rate and the eventual blockage of the conveyor. For group B and D particles, the analysis of Bandrowski & Kaczmarzyk (1981) and Matsumoto *et al.* (1982) shows a similar instability at which the blower characteristic curve intercepts the conveying system characteristic curve tangentially. Furthermore, the gas velocity at this critical point is generally higher than the slugging-type (or classical) choking velocity and can be reduced toward the latter by making the blower characteristic curve steeper (compare AB and A′B′ in figure 1). In gas–liquid co-current upflow systems, a flow "excursion" instability, similar to that in gas–solids systems, has also been identified as resulting from the interaction between pump and conveyor characteristics (Ishii 1982).

Another type of "premature choking" can occur at higher gas velocity than that of classical choking in CFBs, where upflow risers are generally directly coupled with downcomers which return entrained particles to the bottom region of the risers. A pressure balance between the riser and downcomer is required to maintain the system under steady operation. If the gas velocity is

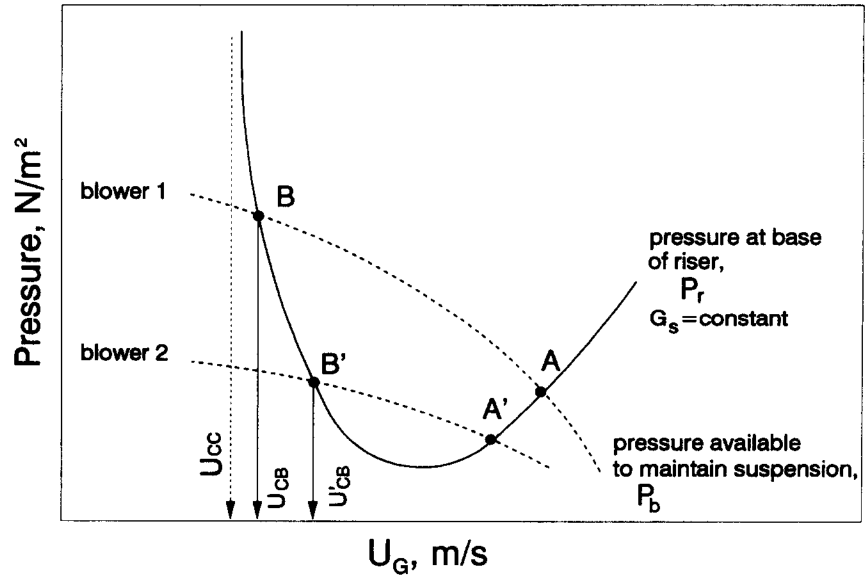

Figure 1. Operational instability due to an insufficient pressure head supplied by the gas blower.

decreased at a given solids circulation rate, a critical state may be reached at which steady operation at a given solids flux becomes impossible; this instability occurs because solids cannot be fed to the riser at the prescribed rate, although slugging may not come into play at this point (Knowlton & Bachovchin 1976; Takeuchi *et al.* 1986; Bai *et al.* 1987; Bader *et al.* 1989; Hirama *et al.* 1992). This critical condition depends on solids inventory in the standpipe, with lower critical velocity for higher solids inventory (Hirama *et al.* 1992; Gao *et al.* 1991). This mode of instability can be circumvented by increasing the solids inventory or standpipe height, or alternatively by uncoupling the riser and the downcomer, e.g. by utilizing a screw feeder as solids feeding system. Such a critical condition is the product of an inappropriate pressure balance between the riser and the downcomer (Bi & Zhu 1993). Such an instability again results from the interaction between auxiliary equipment, in this case the solids return or feed device, and the conveyor. Again, the instability needs to be distinguished from the classical choking condition. We call them equipment-limited modes of choking, type B or "blower-standpipe-induced choking".

The third use of the term choking relates to solids refluxing at the wall of the upward flow column and accumulation of particles in the lower regions.† Chang & Louge (1992) called this third mode "incipient choking". However, we introduce the term "accumulative choking" or, type A choking, to give a better description of the flow pattern transition at this point. Matsen (1982) attributed this mode of choking to an abrupt change in voidage. Such a stepwise change in voidage or pressure drop was also adopted as the mechanism of choking by Yerushalmi & Cankurt (1979), Satija *et al.* (1985), Conrad (1986), Brereton (1987), Rhodes (1989) and Day *et al.* (1990). The stepwise change in bed average voidage can further be attributed to the formation of a dense bed at the bottom of the conveyor. From the viewpoint of solids conveying, this point has been referred to as the minimum transport velocity of the transport line (Thomas 1962; Matsen 1982), because the solids circulation rate at this point is the maximum attainable at a given gas velocity without solids accumulation. The solids circulation rate at this point therefore appears to be the same as the saturation carrying capacity (Zenz & Weil 1958; Wen & Chen 1982; Matsen 1982; Li *et al.* 1992).

Capes & Nakamura (1973) defined choking as the condition under which internal solids circulation begins, with solids moving downward at the pipe wall and upward in the central core. This internal solids circulation may be related to the formation of particle clusters or streamers, but is not necessarily accompanied by any sudden increase in solids concentration or pressure drop (Leung 1980; Matsumoto & Marakawa 1987; Drahos *et al.* 1988; Rhodes 1989). Instead, it has been found that internal solids circulation occurs right after the gas velocity is reduced to reach the minimum pressure drop point (see figure 1) (Leung 1980; Matsumoto & Marakawa 1987; Drahos *et al.* 1988). This velocity is, in turn, analogous to the minimum pressure drop point identified in horizontal transport lines, which coincides with the saltation velocity, where particles are observed to drop out of the suspension and slide along the bottom of the pipe (Thomas 1962; Matsumoto *et al.* 1975; Wirth & Molerus 1986; Geldart & Ling 1992). For vertical flow the velocities corresponding to both the minimum pressure drop and the onset of clustering appear to be somewhat higher than that when particles start to accumulate at the riser bottom (Bi & Fan 1991), and can be considered as the boundary between disperse flow and aggregate flow (Leung 1980).

Other definitions of choking have also been proposed. For example, Briens & Bergougnou (1986) assumed that choking occurs when the annular region at which particles flow downward grows to occupy 25% of the total pipe cross-sectional area. The choice of 25% is arbitrary, especially when one considers that the area occupied by the annular region also varies with axial position. This choking condition also does not correspond to any unstable condition, given that a CFB can operate in a stable manner with the annular solids downflow region occupying as much as 50% of the cross-sectional area (Rhodes 1989; Horio *et al.* 1988; Bader *et al.* 1989).

It is unlikely that such differing definitions could give consistent results. This is indeed the case when one attempts to correlate choking data based on data from authors who have utilized different criteria and definitions to define the choking condition.

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†Note that the accumulation must occur at the bottom of the riser for this type of choking to occur. The increase in solids concentration at the top of a riser with a constricted exit (e.g. Brereton & Grace 1993) penetrates a limited distance downward and does not constitute choking.

Choking Classification and Comparison

As pointed out by Capes & Nakamura (1973), choking is not a single clear-cut phenomenon; instead the term is used to denote a whole range of instabilities. The discrepancy in choking definitions and determinations must play an important role, as noted by some previous investigators (Yerushalmi & Cankurt 1979; Yang 1983; Conrad 1986; Rhodes 1989). However, most investigators proposed new correlations to fit literature data based on different and conflicting definitions. Punwani *et al.* (1976) compared various choking velocity correlations with available experimental data and found that the Yousfi & Gau (1974) equation gave the best prediction of the experimental data of Zenz (1949), Lewis *et al.* (1949) and Ormiston (1969), while seriously underestimating the data of Capes & Nakamura (1973). The correlations of Yang (1975) and Punwani *et al.* (1976) most accurately predict the data of Capes & Nakamura (1973), but overestimate other data. A comparison by Chong & Leung (1986) showed that the Yousfi & Gau (1974) equation fitted the choking data better for Geldart group A and B particles, while the Yang (1975, 1983) equation was recommended for group D particles. Aware of the differences for different kinds of particles, Day *et al.* (1990) treated the slip factor in their model equations in such a way that different correlations were evaluated for different particle categories according to a particle mean size. However, no one has evaluated the equations based on the differences in the definitions of what constitutes choking and the differing assumptions.

Table 1 lists all available choking definitions found in the open literature and corresponding regime transition definitions obtained in gas–solids vertical upflow systems for the purpose of comparison and classification. All the definitions can be classified into the three categories described above, depending on the phenomena observed and definitions of choking employed. Type C, or classical choking, corresponds to the occurrence of slug flow and inherent severe instability. Type B, or blower-/standpipe-induced choking, corresponds to a marginal instability condition in which the bed collapses, either because an inadequate pressure balance is built up in the whole unit so that solids cannot be fed to the riser at the prescribed rate, or because the blower can no longer provide the pressure drop required to support the material. Type A, or accumulative choking, is characterized by the appearance of a dense bed at the bottom of the riser, stepwise changes in bed voidage and pressure drop, and solids downflow at the wall.

The most popular choking correlations of Leung *et al.* (1971), Yousfi & Gau (1974), Yang (1975, 1983), Punwani *et al.* (1976) and Matsen (1982), as well as the recent equation of Bi & Fan (1991), all listed in table 2, are compared with the literature data in table 3. Calculated root-mean-square relative deviations (RMS) in the predicted choking velocities are given in table 4. It can be seen that for the type C choking velocity, the Yousfi & Gau (1974) correlation, evaluated from the experimental data of Lewis *et al.* (1949), Zenz (1949) and Ormiston (1969), as well as their own data, gives the best prediction. All other equations overestimate the experimental data. All of the data used to derive this condition correspond to transition to slug flow; the other definitions of choking should all give higher values.

The type B choking velocity, mainly resulting from the restriction of the pressure balance in the whole system, is found to be somewhat higher than the prediction of the Yousfi & Gau (1974) equation, but lower than the prediction of Bi & Fan (1991), Yang (1975, 1983) and Punwani *et al.* (1976). None of these equations gives good predictions of this transition velocity, as can be seen in table 4. It appears that the type B choking condition generally occurs between the type C, or classical choking, and type A, or accumulative choking, conditions. Deviations are generally higher, not surprising in view of the fact that blower characteristics and external standpipe conditions, not included in the correlations, played important roles for these data.

The type A choking velocity is sometimes also called the minimum transport velocity of the conveyor. The solids circulation rate at this point corresponds to the saturation carrying capacity (Zenz & Weil 1958; Wen & Chen 1982; Sciazko *et al.* 1991). Table 4(c) shows that the Yang (1975, 1983) equation gives satisfactory agreement with the literature data, while the Bi & Fan (1991) equation, which was based on most of these data, predicts these data most accurately. The Yousfi & Gau (1974) equation is found to underpredict the data.

Table 1. Summary of choking definitions

Author	Definition
	(a) Classical (Type C) Choking Definition
Zenz (1949)	Slugging occurs to such extent that stable operation ceases
Lewis (1949)	Termination of steady operation due to slug formation
Ormiston (1969)	Bed collapses into slugging state
Yousfi & Gau (1974)	Solids slugs extend over the entire pipe cross-section
Drahos *et al.* (1988)	Formation of slugging dense bed
Mok *et al.* (1989)	Transport line is plugged
Bi *et al.* (1991)	Slugging occurs to such extent that stable operation ceases
Chang & Louge (1992)	Loud banging noises and shaking of the riser resulting from the passage of slugs
	(b) Blower-/Standpipe-induced (Type B) Choking Definitions
Knowlton & Bachovchin (1976)	Solids flux can no longer be maintained at the prescribed rate
Bandrowski & Kaczmarzyk (1981)	System becomes unstable due to the gas blower being unable to support the transport line
Matsumoto *et al.* (1982)	Substantial transport of solids becomes impossible because the gas blower cannot support the transport line
Takeuchi *et al.* (1986)	Solids flux can no longer be maintained at the prescribed rate
Bai *et al.* (1987)	Solids flux can no longer be maintained at the prescribed rate
Bader *et al.* (1989)	Steady operation at the given solids flux becomes impossible
Schnitzlein & Weinstein (1988)	Maximum solids flux attainable at a given gas velocity
Gao *et al.* (1991)	Same as Schnitzlein & Weinstein (1988)
Horio *et al.* (1992)	Same as Schnitzlein & Weinstein (1988)
Hirama *et al.* (1992)	Solids flux can no longer be maintained at the prescribed rate
	(c) Accumulative (Type A) Choking Definitions
Yerushalmi & Cankurt (1979)	Stepwise change in pressure drop
Matsen (1982)	Stepwise change in bed voidage due to the formation of clusters of particles
Yang (1983)	Slight decrease of transport velocity at the same solids rate will increase the pressure drop in the transport line exponentially, which provides a demarcation between the dilute-phase pneumatic transport and the fast fluidization regime
Satija *et al.* (1985)	Step change in bed voidage
Chong & Leung (1986)	Stepwise transition from dilute-phase uniform suspension to dense-phase non-uniform suspension
Takeuchi *et al.* (1986)	Density difference between the top and bottom of the column starts to appear
Conrad (1986)	Termination of uniform suspension flow
Brereton (1987)	Solids start to accumulate in the bottom of the riser
Drahos *et al.* (1988)	Particles start to accumulate at the bottom of the column due to the imbalance between the solids feed rate and the transport capacity of the gas
Rhodes (1989)	Sudden increase in solids concentration and amplitude of pressure fluctuation
Day *et al.* (1990)	The axial voidage variation at the inlet of the column appears
Chang & Louge (1992)	Suspension collapse and a denser region starts to form at the bottom of the riser
Li *et al.* (1992)	Sudden change in flow structure from dilue-phase to dense-phase transport; the velocity corresponds to the saturation carrying capacity of the system

To summarize, three distinct types of choking initiation mechanisms have been identified. The lowest (type C or classical) results in a severe slugging condition in the transport line; the second (type B or blower-/standpipe-induced) depicts an instability resulting from gas blower–conveyor interaction and/or solids feeder–conveyor interaction in the system; the third (type A or accumulative) denotes a transition from a condition when all particles are traveling upwards with little or no axial variation to a mode where there are solids downflow at the wall and accumulation of a dense phase at the bottom. For practical applications, the most undesirable condition in a commercial system is the instability of operation. It is therefore practical to consider the classical choking as the lowest critical choking transition, while type B choking may occur first when there are blower or standpipe limitations. Accumulative choking, corresponding to the onset of a dense region at the riser bottom, should not be confused with the other two transitions which represent operational limitations. With decreasing gas velocity, type A choking will occur first, followed by type B (if there are significant blower or feeder limitations) or otherwise by type C choking for slugging systems.

CHOKING PREDICTIONS

Many equations have been developed to predict the choking velocity based on different assumptions (Marcus *et al.* 1990). The correlation of Leung *et al.* (1971) was obtained by assuming that at choking the relative velocity between gas and particles is equal to the free-fall or terminal velocity of single particles, and that the choking voidage is equal to 0.97. In the equation of Yang (1975) the relative velocity was also assumed to equal the terminal velocity of single particles, while the solids-to-tube wall friction factor was taken as a constant [0.01, estimated from the experimental data of Hariu & Molstad (1949)]. The choking data of Capes & Nakamura (1973) were used to validate the model. However, it was found that another constant friction factor, 0.04, had to be used to fit other choking data. To correlate other literature data, Yang (1983) later modified the friction factor to be dependent on the ratio of gas and solids densities; Punwani *et al.* (1976), on the other hand, modified the choking friction factor of Yang (1975) by including a gas density effect to fit the high-pressure choking data of Knowlton & Bachovchin (1976). The equations of Yousfi & Gau (1974) and Knowlton & Bachovchin (1976) are purely empirical. The former was derived from the experimental data of Zenz (1949), Lewis *et al.* (1949), Ormiston (1969) and Yousfi & Gau (1974), in which choking was defined by the slug flow condition; the latter was obtained by correlating the only high-pressure choking data, those of Knowlton & Bachovchin (1976), in which the riser was coupled with a downcomer and the particles were of wide size distributions.

As evaluated above, no equation can be used to predict all three types of choking velocities. Hence, separate approaches for predicting the onset of each type of choking are required.

Type A: Accumulative Choking Velocity, U_{CA}

The minimum transport velocity, which corresponds to the accumulative choking velocity, U_{CA}, is an important parameter for pneumatic transport and for particle entrainment in the freeboard. From the pneumatic transport point of view, it sets the minimum superficial gas velocity required to make a given flux of solid particles fully suspended in the whole transport line without accumulation. U_{CA} is related to the solids elutriation rate from the top of the bed. A number of correlations have been proposed to calculate the entrainment from fluidized beds operated at relatively low gas velocities ($U_G < 1$ m/s) (e.g. Wen & Chen 1982; Geldart 1986) or at somewhat higher gas velocities ($U_G < 4$ m/s) (e.g. Zenz & Weil 1958; Sciazko *et al.* 1991). However, there are no correlations which can be reliably extended to the high velocity range.

Table 2. Equations used in the comparison of choking velocity, U_{Ch}

Leung *et al.* (1971)	$U_{Ch} = 32.3\dfrac{G_s}{\rho_s} + 0.97V_t$	[1]
Matsen (1982)	$U_{Ch} = 10.74V_t\left(\dfrac{G_s}{\rho_s}\right)^{0.227}$	[2]
Yousfi & Gau (1974)	$\dfrac{U_{Ch}}{\sqrt{gd_p}} = 32\,\mathrm{Re}_t^{-0.06}\left(\dfrac{G_s}{\rho_G U_{Ch}}\right)^{0.28}$	[3]
Yang (1975, 1983)	$\dfrac{2gD_t(\varepsilon_{Ch}^{-4.7} - 1)}{\left(\dfrac{U_{Ch}}{\varepsilon_{Ch}} - V_t\right)^2} = 6.81 \times 10^5\left(\dfrac{\rho_G}{\rho_s}\right)^{2.2}$	[4]
Punwani *et al.* (1976)	$\dfrac{2gD_t(\varepsilon_{Ch}^{-4.7} - 1)}{\left(\dfrac{U_{Ch}}{\varepsilon_{Ch}} - V_t\right)^2} = 0.008743\rho_G^{0.77}$	[5]
Bi & Fan (1991)	$\dfrac{U_{Ch}}{\sqrt{gd_p}} = 21.6\left(\dfrac{G_s}{\rho_G U_{Ch}}\right)^{0.542}\mathrm{Ar}^{0.105}$	[6]

Ar = Archimedes number, $\rho_G(\rho_s - \rho_G)gd_\rho^3/\mu_G^2$, d_p = mean particle dia, D_t = column dia, g = acceleration of gravity, G_s = solids circulation rate, Re_t = terminal Reynolds number = $\rho_G d_p V_t/\mu_G$, V_t = particle terminal settling velocity, ε = overall voidage at choking point, μ_G = gas viscosity, ρ_G = gas density, ρ_s = solids density.

Table 3. Summary of studies on choking velocity

Reference	Solids	d_p (μm)	ρ_s (kg/m^3)	D_t (mm)	H (m)	Type of feeder
	(a) Classical (Type C) Choking Velocity					
Zenz (1949)	Salt	168	2098	44.5	1.2	Hopper
	GB	587	2483	44.5		
	Sand	930	2643	44.5		
	Rape seed	1676	1089	44.5		
Lewis *et al.* (1949)	GB	40	2483	31.8	3.0	Hopper
	GB	100	2483	31.8		
	GB	280	2483	31.8		
Ormiston (1969)	Sand	120	2659	25.4	5.5	Hopper
	Sand	151	2659	25.4		
	Sand	225	2659	25.4		
	Sand	265	2659	25.4		
Yousfi & Gau (1974)	Sand	118	2470	50	6.0	Fluidized bed
	Sand	143	2470	50		
	Sand	183	2470	50		
	PE	290	1060	50		
Drahos *et al.* (1988)	Phosphate	120	2550	55	2.23	Screw feeder
	Phosphate	200	2550	55		
Mok *et al.* (1989)	Sand	210	2620	20	9.0	Fluidized bed
Bi *et al.* (1991)	PE	325	660	102	6.4	Standpipe $D_d/D_t = 1$
	(b) Blower-/Standpipe-induced (Type B) Choking Velocity					
Knowlton & Bachovchin (1976)	Siderite	157	2384	76.2	15.0	Standpipe
	Lignite	363	747	76.2		
Bandrowski & Kaczmarzyk (1981)	Sand	400	2500	20		Hopper
Matsumoto & Marakawa (1987)	GB	1030	2500	20	5.6	Hopper
	GB	1960	2500	20		
	GB	2970	2500	20		
Takeuchi *et al.* (1986)	FCC	57	1050	100	5.5	Standpipe $D_d/D_t = 2.0$
Bai *et al.* (1987)	FCC	94	1646	186	8.4	Standpipe $D_d/D_t = 1.6$
	Silicagel	187	703	186		
	Silicagel	603	790	186		
	Silicagel	1041	1303	186		
	Coal	939	2200	186		
	Sand	78	2660	186		
	Sand	652	2660	186		
Bader *et al.* (1989)	Catalyst	76	1714	305	12.2	Standpipe $D_d/D_t = 1$
Schnitzlein & Weinstein (1988)	FCC	59	1450	152	8.4	Standpipe $D_d/D_t = 2.2$
Gao *et al.* (1991)	FCC	62	1020	90	8.4	Standpipe $D_d/D_t = 2.2$
	Catalyst	82	1780	90		
Horio *et al.* (1992)	FCC	60	1000	200	1.6	Standpipe $D_d/D_t = 2.0$
	Sand	106	2600	200	1.6	
Hirama *et al.* (1992)	FCC	54	750	100	5.5	Standpipe $D_d/D_t = 2.0$
	FCC	69	930	100		
	(c) Accumulative (Type A) Choking Velocity					
Yerushalmi & Cankurt (1979)	FCC	49	1070	152	8.5	Standpipe
	HFZ-20	49	1450	152		
Chen *et al.* (1980)	Iron ore	105	4510	90	9.0	Standpipe
	Alumina	81	3090	90		
	Iron ore	56	3050	90		
	FCC	58	1780	90		
Satija *et al.* (1985)	Sand	155	2446	102	6.5	Standpipe
	Sand	245	2446	102		
Takeuchi *et al.* (1986)	FCC	57	1050	100	5.5	Standpipe
Bi (1988)	FCC	48	1450	186	8.4	Standpipe
	Sand	31	2650	186		
	Silicagel	140	760	186		
	Silicagel	280	760	186		
Drahos *et al.* (1988)	Phosphate	120	2550	55	2.23	Screw feeder
Mok *et al.* (1989)	Sand	210	2620	20	9.0	Fluidized bed
Bi *et al.* (1991)	PE	325	660	102	6.5	Standpipe
Chang & Louge (1992)	Plastic grit	234	1440	200	7.0	Standpipe
	Steel grit	67	7400	200	7.0	

FCC = fluid catalytic cracking catalyst; GB = glass beads; PE = polyethylene; d_p = mean particle dia; D_d = standpipe dia; D_t = column dia; H = total height of riser; ρ_s = solids density.

Table 4. Comparison between experimental data and choking predictions

Data source	No. of data	RMS relative deviation of experimental data†					
		1‡	2	3	4	5	6
(a) Classical (Type C) Choking Velocity							
Zenz (1949)	18	0.768	5.625	0.298	0.926	0.866	1.22
Lewis *et al.* (1949)	21	0.385	1.277	0.083	0.264	0.262	0.768
Ormiston (1969)	12	0.294	1.808	0.098	0.244	0.193	1.174
Drahos *et al.* (1988)	13	0.323	0.974	0.063	0.224	0.211	0.299
Mok *et al.* (1989)	6	0.236	1.635	0.104	0.117	0.211	0.299
Bi *et al.* (1991)	4	0.460	0.932	0.053	0.216	0.058	0.166
Total	**74**	**0.470**	**3.126**	**0.160**	**0.490**	**0.456**	**0.905**
(b) Blower-/Standpipe-induced (Type B) Choking Velocity							
Knowlton & Bachovchin (1976)	24	0.660	0.583	0.872	0.647	0.634	0.602
Bandrowski & Kaczmarzyk (1981)	2	0.536	1.626	0.711	0.285	0.360	0.090
Matsumoto & Marakawa (1982)	12	0.082	3.731	0.542	0.126	0.102	0.360
Takeuchi *et al.* (1986)	6	0.437	0.798	0.063	0.633	0.277	0.139
Bai *et al.* (1987)	38	0.446	2.512	0.265	0.499	0.406	0.570
Bader *et al.* (1989)	3	0.494	0.805	0.597	0.563	0.369	0.090
Schnitzlein & Weinstein (1988)	6	0.447	0.814	0.392	0.252	0.081	0.332
Gao *et al.* (1991)	62	0.427	0.478	0.244	0.362	0.266	0.171
Horio *et al.* (1992)	17	0.539	0.519	0.459	0.485	0.372	0.292
Hirama *et al.* (1992)	4	0.434	0.811	0.472	1.03	0.861	0.231
Total	**174**	**0.457**	**1.563**	**0.436**	**0.475**	**0.380**	**0.388**
(c) Accumulative (Type A) Choking Velocity							
Yerushalmi & Cankurt (1979)	5	0.818	0.874	0.230	0.226	0.235	0.112
Chen *et al.* (1980)	12	0.755	0.555	0.472	0.378	0.245	0.165
Satija *et al.* (1985)	4	0.524	0.523	0.430	0.207	0.285	0.291
Takeuchi *et al.* (1986)	7	0.581	0.838	0.244	0.258	0.178	0.118
Drahos *et al.* (1988)	5	0.595	0.058	0.348	0.351	0.410	0.094
Bi (1988)	15	0.571	0.638	0.533	0.144	0.304	0.488
Mok *et al.* (1989)	9	0.440	0.733	0.428	0.369	0.406	0.299
Bi *et al.* (1991)	4	0.540	0.556	0.192	0.050	0.174	0.267
Chang & Louge (1992)	10	0.578	0.371	0.444	0.316	0.362	0.200
Total	**71**	**0.576**	**0.439**	**0.390**	**0.266**	**0.292**	**0.240**

†$\mathrm{RMS} = \left[\frac{1}{N-1}\sum\left(\frac{U_{\mathrm{Ch,cal}} - U_{\mathrm{Ch,exp}}}{U_{\mathrm{Ch,exp}}}\right)^2\right]^{1/2}$ where N = number of data, U_{Ch} = superficial velocity at choking, and cal and exp refer to calculated and experimental values, respectively.

‡1–6 correspond to [1]–[6] in table 2.

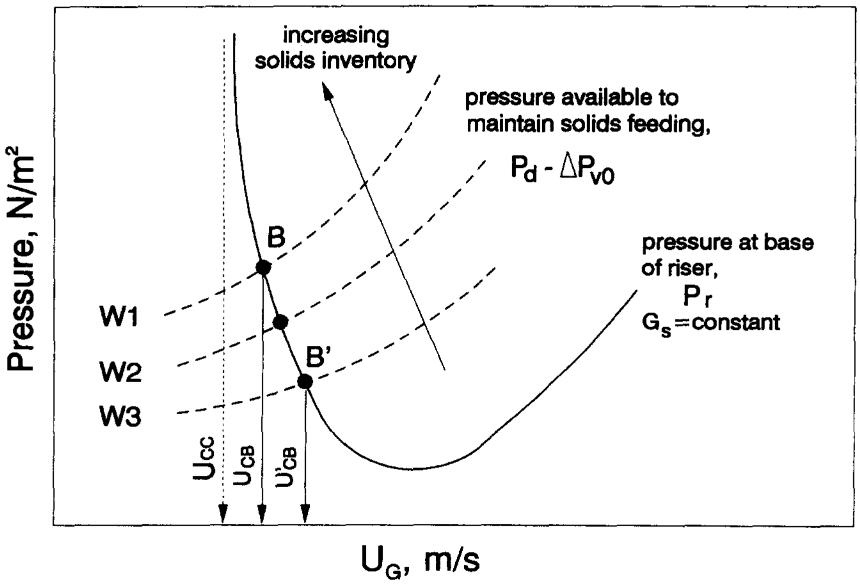

Figure 2. Operational instability due to an imbalance of pressures at the base of the riser (P_r) and downcomer (P_d). U_{CB} and U_{CC} correspond to type B and C choking velocities; U_G = superficial gas velocity; W = total solids inventory; $\triangle P_{v0}$ = pressure drop across fully open solids control valve.

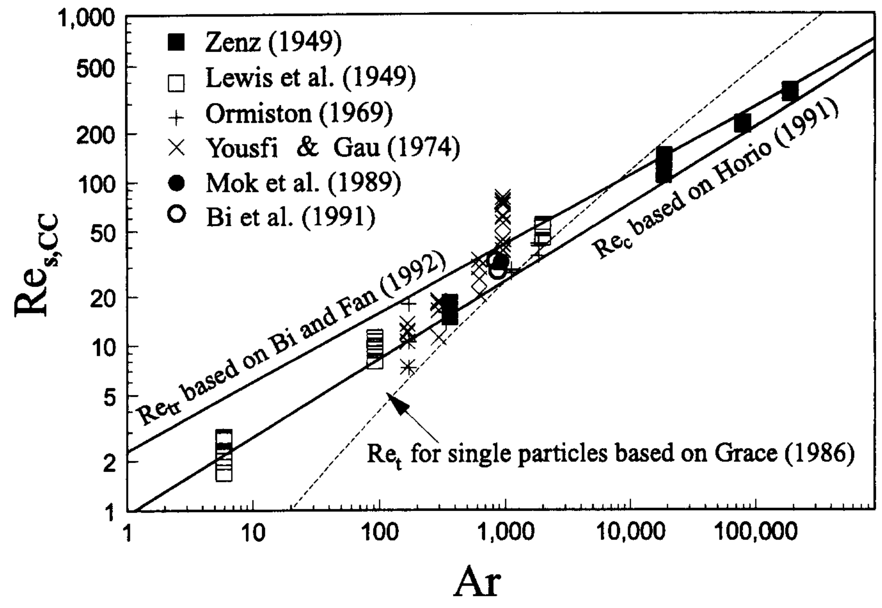

Figure 3. Reynolds number based on the relative velocity at the classical choking point, $Re_{s,CC}$, as a function of Archimedes number, Ar, compared with Reynolds number corresponding to maximum amplitude of pressure fluctuations (Re_C), terminal settling velocity of single particles (Re_t) and transport velocity (Re_{tr}).

When the gas velocity is reduced to below the accumulative choking point, all particles can no longer be fully suspended in the riser. The dilute-phase transport therefore collapses and a dense bed forms at the bottom of the riser. It is important to find out what causes the dilute suspension to collapse at this transition point. Yang (1975) suggested that the solids–wall friction approaches a constant (0.01) at this transition point based on the data of Hariu & Molstad (1949). Matsen (1982) attributed the collapse of dilute-phase suspensions to the formation of particle clusters. Louge *et al.* (1991), on the other hand, postulated that this collapse occurs when the particle weight overcomes gas shear in a global momentum balance. Day *et al.* (1990) modeled this choking process as corresponding to no axial voidage variation at the inlet of the riser, reflecting the absence of particle accumulation at the bottom of the riser when the gas velocity exceeds the accumulative choking velocity. Until the mechanism of suspension collapse is understood, it is recommended that the Yang (1975, 1983) and Bi & Fan (1991) equations, both of which are based on the accumulative choking definition and/or experimental data, be used to predict this velocity.

Type B: Blower-/Standpipe-induced Choking Velocity, U_{CB}

(a) Conveyor–blower interaction

Centrifugal blowers are characterized by reducing volumetric delivery with increasing delivery pressure. For a blower of given power, there is a maximum gas velocity corresponding to a given pressure head (Wen & Galli 1971). The typical pressure drop vs gas flow rate characteristic curves are generally provided by the supplier for a given gas blower. The critical condition can thus be determined as indicated in figure 1 (Doig & Roper 1963; Leung *et al.* 1971; Bandrowski & Kaczmarzyk 1981; Matsumoto *et al.* 1982; Dry & LaNauze 1990).

(b) Conveyor–feeder interaction

In a conveyor accompanied by a solids return device, such as a standpipe in a CFB, a pressure balance is reached between the riser and the standpipe when the particles in the downcomer are fluidized (Kwauk *et al.* 1986; Yang 1989; Rhodes & Geldart 1989). Key components of a typical CFB unit are the riser, a downcomer, a solids control valve and a gas–solids separator/cyclone. For a given solids inventory, solids circulation rate and superficial gas velocity, the pressure head at the bottom of the riser, P_r, and the bottom of the downcomer, P_d, are each predetermined when the unit is under steady operation. The pressure drop across the solids control valve, ΔP_v, is thus adjusted to be equal to $P_d - P_r$. However, when the solids control valve has been completely opened, a further increase in P_r by reducing the superficial gas velocity makes $P_d - P_r$ smaller than the fully open valve pressure drop, ΔP_{vO}. The system then cannot remain at steady state at the prescribed solids circulation rate. Such a process is illustrated in figure 2. The solid line represents the characteristic curve of P_r. The dashed lines represent the maximum available pressure head from the downcomer, $P_d - \Delta P_{vO}$. As the gas velocity is reduced toward U_{CB}, the pressure drop across the control valve is adjusted to meet the requirement for pressure balance in the whole loop, i.e. $\Delta P_v = P_d - P_r$. However, beyond a certain point, the pressure drop across the solids control valve cannot be reduced further, either because the valve has been completely opened or the aeration air no longer has any effect. In this case, either the gas velocity in the riser needs to be raised to maintain the bed under steady operation at the prescribed solids circulation rate or the solids circulation rate will sharply decrease while the gas velocity remains the same. The former corresponds to the maximum solids circulation rate identified by Schnitzlein & Weinstein (1988), Gao *et al.* (1991) and Horio *et al.* (1992), while the latter represents the critical condition identified by Takeuchi *et al.* (1986) and Bai *et al.* (1987). Such an instability analysis, as shown recently by Bi & Zhu (1993), successfully predicts the experimental data of Hirama *et al.* (1992) and Gao *et al.* (1991).

Type C: Classical Choking Velocity, U_{CC}

Classical choking is considered to occur as the gas velocity is reduced when slug flow commences to such an extent that stable operation as a dilute suspension becomes impossible (Zenz 1949). The slugging is the same as that which occurs when the gas velocity is increased in a conventional bubbling fluidized bed of small diameter. In a batch system, bubble behavior is dependent on the superficial gas velocity. In a continuous system, on the other hand, bubble behavior depends on the relative motion between the gas and solids phase instead of on the superficial gas velocity. The apparent relative velocity at choking, is

$$U_{s,CC} = U_{CC} - \frac{G_{s,CC}\varepsilon_{CC}}{\rho_s(1-\varepsilon_{CC})}, \qquad [1]$$

where $G_{s,CC}$ and ε_{CC} are the solids circulation flux and overall voidage at the classical choking condition. In a fluidized bed with increasing gas flow, the most unstable condition should occur around the velocity, U_c, which corresponds both to the beginning of the transition from bubbling/slugging to turbulent fluidization and to bubbles of maximum size. Above the transport velocity, U_{tr}, all bed particles become transportable and the absence of a dense bed prevents the formation of gas bubbles.

Table 5. Criteria for distinguishing slugging and non-slugging systems

Authors	Proposed mechanism	Equations for slugging	Comments
Yousfi & Gao (1974)	Stability of upward flow of a uniform unbounded suspension	$\frac{V_t^2}{gd_p} > 140$	No allowance for wall effects
Yang (1975)	Slug stability based on the equation of Harrison *et al.* (1961)	$\frac{V_t^2}{gD_t} > 0.35$	Based on bubble splitting from the rear
Geldart (1977)	Slug stability based on empirical evidence	$\frac{V_t'^2}{gD_t} > 0.3$, where V_t' is based on particles of diameter $2.7d_p$	
Smith (1978)	Slugs postulated to not be able to rise faster than porosity waves	$\frac{V_t\varepsilon^{n-1}n(1-\varepsilon)}{\sqrt{gD_t}} > 0.41$	
Guedes de Carvalho (1981)	Slug stability based on a modified Harrison *et al.* (1961) equation	$\frac{\rho_G\mu_G D_t^{0.5}}{(\rho_s-\rho_G)^2 d_p^2 g^{0.5}} > \left(\frac{A}{0.66}\right)^4$	Based on bubble splitting from the rear

A is a constant introduced by the author; n is the Richardson & Zaki constant; ε is the overall bed voidage.

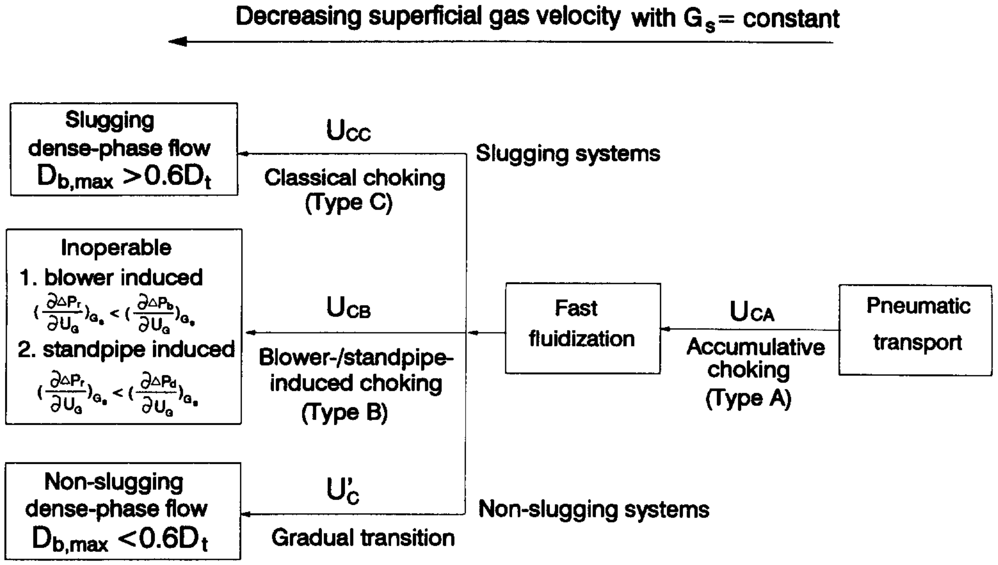

Figure 4. Flow chart showing the transitions between dense-phase transport, fast fluidization and pneumatic transport with decreasing gas flow and constant solids flux. $D_{b,max}$ = maximum stable bubble dia; ΔP_b = pressure drop provided by blower; ΔP_d = pressure drop across standpipe; ΔP_r = pressure drop across riser.

The reported classical choking velocity data of Zenz (1949), Lewis *et al.* (1949), Ormiston (1969), Yousfi & Gau (1974), Mok *et al.* (1989) and Bi *et al.* (1991) are plotted as $Re_{s,CC}$ vs Ar in figure 3. For comparison, Reynolds numbers corresponding to U_c (Horio *et al.* 1992), U_{tr} (Bi & Fan 1991) and the terminal velocity of single particles (Grace 1986) are also plotted. It is seen that most experimental data lie between Re_c and Re_{tr}. We see that $U_{s,CC}$ ranges from U_c to U_{tr}, depending on particle properties and unit structure. This implies that classical choking represents a range of instability instead of a single point, even though this choking has been defined as the state when slug flow must come into play. Until more experimental data are generated and the classical choking mechanism is more clearly understood, the Yousfi & Gau (1974) equation, correlated from the classical choking data of Zenz (1949), Lewis *et al.* (1949), Ormiston (1969) and Yousfi & Gau (1974), can be used to estimate this choking velocity.

Slugging vs Non-slugging Systems

Not all systems are capable of slugging. If the particles are relatively small or the riser diameter is relatively large, void diameters do not approach the riser diameter due to splitting. Under these circumstances, there can be no transition to slug flow and the system can be said to be a non-slugging system (Zenz 1949; Yousfi & Gau 1974; Yang 1976; Leung 1980). Although classical choking cannot occur in such systems, types B and A choking can still occur.

Several different criteria have been proposed to distinguish between slugging and non-slugging systems. They are listed in table 5. Since they are based on different concepts and since there is considerable uncertainty regarding the mechanism of bubble splitting and the factors which control maximum void size, the criteria are not widely accepted. For example, several of the criteria in table 5 are based on the concept of bubble splitting from the rear, whereas there is considerable evidence (e.g. Rowe & Partridge 1965; Clift & Grace 1972; Upson & Pyle 1973) that the splitting occurs from the front. Improved understanding is needed before there are reliable methods which distinguish slugging from non-slugging systems.

RELATIONSHIP BETWEEN CHOKING AND FLOW REGIME TRANSITIONS

CFBs have been widely utilized in the past two decades. The provision of a standpipe which allows particles to be returned to the bottom of the riser makes a CFB system capable of being operated from conventional fluidization (bubbling, slugging) right through to the pneumatic transport regime. A CFB is, however, generally operated in the so-called fast fluidization regime which is usually characterized by a denser region at the bottom of a riser and a more dilute region above, with no sharp interface between these two regions. With increasing gas velocity, the transition from fast fluidization to pneumatic transport corresponds to the saturation carrying point, minimum transport velocity or accumulative choking velocity, beyond which all particles are transported up the riser, with no particle accumulation at the bottom. The termination of fast fluidization when reducing gas flow to dense-phase transport is commonly said to be demarcated by the choking velocity. Clearly this must be one of the other choking velocities (type B or C).

Figure 4 gives a flow chart showing the possible flow regimes and regime transitions in gas–solids cocurrent upward flow systems. The boundary between dilute-phase flow and fast fluidization is set by the type A or accumulative choking velocity or minimum transport velocity. The transition from fast fluidization to the dense-phase flow regimes depends on the particle properties and on the physical equipment, since the transition corresponds to one of three conditions—type B or blower-/standpipe-induced choking, type C or classical choking or (for non-slugging systems) U'_C. When there are gas blower and/or solids feeder limitations, the fast fluidization regime terminates to an inoperable regime at the type B or blower-/standpipe-induced choking velocity. For a slugging system, fast fluidization may transform to slugging dense-phase flow at the type C or classical choking velocity. In non-slugging systems where type C or classical choking does not exist, if sufficient pressure heads are provided by both the gas blower and the solids feeder, then steady bubbling dense-phase flow operation can be realized (Yousfi & Gau 1974; Hirama *et al.* 1992). The transition from fast fluidization to non-slugging dense-phase flow in such a case occurs gradually. Some characteristic is then needed to define the boundary between these two regimes. This transition can be considered to occur when the bottom dense region fills up the entire riser as the gas velocity is reduced at a fixed solids flow rate. Our comparison in figure 3 suggests that choking may occur between U_c and U_{tr}, involving a transition to a dense-phase flow. As a first estimate, one can also use U_c to quantify this transition.

CONCLUSIONS

Three different types of choking have been identified. Type A (accumulative) choking occurs as the gas velocity is reduced for all systems when local refluxing (downward motion) of particles begins to such an extent that a dense region is formed at the bottom. Type B (blower-/standpipe-induced) choking takes place when either the blower is incapable of providing sufficient pressure head to maintain all the particles in suspension or when the standpipe which returns solids to the base of the riser is incapable of supplying the required flow of particles. This type of choking can be avoided by proper design of the blower and standpipe and by maintaining an adequate inventory of solids or by uncoupling the riser and the solids feed system. Type C (classical) choking occurs only for slugging systems, i.e. systems where bubbles can grow to a size comparable with the riser

Table 6. Summary of types of choking

Type	Manifestation	Means of avoidance or restrictions	Prediction
A—Accumulative	Some particles begin to move downward, i.e. refluxing begins, and a dense phase forms at the bottom	None	Yang (1975, 1983) or Bi & Fan (1991)
B—Blower-/standpipe-induced	Catastrophic shutdown as blower is incapable of maintaining flow or as standpipe is incapable of supplying enough solids to balance the entrainment	Larger blower, increased solids inventory, taller standpipe or uncoupling solids feed system	Matsumoto *et al.* (1982) as in figure 1 for blower-induced; Bi & Zhu (1993) as in figure 2 for standpipe-induced
C—Classical	Severe slugging in a dense phase begins	Not an outcome for non-slugging systems, i.e. if riser diameter is significantly larger than largest voids	Yousfi & Gau (1974)

internal diameter. In this case, severe slugging occurs as the gas velocity is reduced for a conveyed suspension. The three types are summarized in table 6.

The boundary between fast fluidization and pneumatic transport is set by the type A choking velocity/minimum transport velocity, while the transition from fast fluidization to slugging dense-phase flow is demarcated by the type C or B choking velocities, whichever is greater. The transition from fast fluidization to non-slugging dense-phase flow for small particles in large-diameter units where voids cannot grow to fill the column occurs when the bottom dense region develops to occupy the whole riser. According to this definition, two flow regimes may be present in the bottom dense region of the riser depending on particle properties and the physical nature of the blower, standpipe and riser. For small particles in large-diameter units slugging and classical choking do not exist. However, for large particles in small-diameter units, slug-like structures can occur periodically in the bottom dense region, causing the transition between dense-phase conveying and fast fluidization to be diffuse rather than abrupt.

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