Control Mechanisms of Fluidized Solids Circulation Between Adjacent Vessels

Many industrial processes require the circulation of particles between reacting fluidized compartments at a stable, but flexible rate, so that the processes can be operated at different solids rates. In order to understand the phenomena involved in the circulation and its control, circulation of sand particles has been studied through a new experimental approach, using an open-loop two compartment circulating system.

Experimental results show that the control of the circulation rate depends on three phenomena: the vertical resisting force in the fluidized compartments, the contraction of flow in the communication zone, and the bypass of gas between the compartments. For industrial purposes, the first appears to be predominant in the control of the solids rate. The second ensures neither the strict control of this rate nor the required flexibility. The link between the gas bypass and the circulation phenomena is explained and recommendations for the design and operation of circulating systems are given.

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Introduction

The petroleum industry has contributed to the development of the first systems involving the circulation of particles between two reactors through inclined pipes. These applications are known as fluidized catalytic cracking (FCC) and thermal cracking and have been described elsewhere (Kunii and Levenspiel, 1968, and Kunii, 1980). More recently, because of the economical conditions, more compact systems have appeared. They are used mainly for the gasification of coal and biomass, and they are generally made of several fluidized compartments. Examples of such concepts are the draft-tube (Yang and Keairns, 1975, 1978, 1983; LaNauze and Davidson, 1975; LaNauze, 1976; Hofbauer, 1983; Judd et al., 1983, 1986; Escudero et al., 1985, and Button and Delcoigne, 1985), the two-compartment auto-circulating fluidized boiler (Ndenge, 1985) and the four-compartment reactor invented by Kunii (Kuramoto et al., 1981, 1985). These authors showed the existence of a driving force, of two kinds of resisting mechanisms, and of a gas bypass phenomenon. They also published several empirical correlations, in order to help the designers of circulating systems. Despite the great number of studies made of such systems, the phenomena involved in the circulation of solids and its control are not well understood and the design and operation of circulating systems based on published results remains risky.

This paper presents a new theoretical and experimental approach which aims at giving recommendations for proper design and operation of circulating systems, based on the better understanding of the phenomena involved in the circulation of fluidized particles between vessels. The proper adjustment of the aeration rate of the downflowing compartment proved to be the most powerful and versatile tool for the control of the circulation rate.

Literature Survey

In the early 1980's, Kunii invented a new type of reactor to be used for the economical gasification of biomass and municipal wastes which is made of four compartments: two reacting compartments (gasification and combustion) separated from each other by two inert compartments. Heat is transferred from the exothermic to the endothermic compartment by means of heat carrying particles. Details on this reactor will be found in Kuramoto et al. (1981, 1985). The required operating conditions (value of the circulation rate of solids) can be achieved by proper adjustment of the aeration rates in the four compartments (i.e., eight aeration rates).

The draft-tube system is similar in its principle to the four-compartment system, but is made of only two reacting compart-

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ments which are separated by the wall of the central tube. In this concept too, the required level of the circulation rate of solids is achieved by proper adjustment of the aeration rates in the draft-tube and in the downflowing annulus.

These compact systems have the following advantages:

- Easy to obtain circulation
- Stable circulation rate of solids
- Real operating flexibility

A great deal of experimental results have been published so far (Yang and Keairns, 1975, 1978, 1983; LaNauze and Davidson, 1975; LaNauze, 1976; Hofbauer, 1983; Judd et al., 1983, 1986; Escudero et al., 1985; Botton and Delcoigne, 1985; Ndenge, 1985, and Kuramoto et al., 1981, 1985). From the point of view of the hydrodynamic behavior, essential results have been obtained. First of all, the phenomenon of circulation has been examined in terms of the equilibrium between driving and resisting forces. The origin of the driving force is generally attributed to the density difference between the compartments, which is maintained by means of differential aeration between them. Concerning the resisting force, two causes have been found:

- The friction of particles against the vertical walls in the compartments
- The contraction of the flow of the gas-solids mixture in the zone of communication between two compartments

Some authors found the first one to be predominant (LaNauze and Davidson, 1975, and LaNauze, 1976), while others attributed the most efficient effect on the control of the circulation rate of solids to the second one (Kuramoto et al., 1986). In fact, LaNauze neglected the resistance in the communication zone of his draft-tube system, but found a significant effect on the circulation rate of solids by the distance between the distributor and the inlet of the draft. This seemingly contradictory result shows that the phenomena involved in the circulation of particles and its control are not well understood. However, this point is of crucial importance since it will have considerable consequences for the way circulating systems will be designed. If the first mechanism (wall-particles friction) is the most important in the control of the circulation rate of solids, then this control will be achieved through the adjustment of operating variables only. On the other hand, if the second mechanism prevails, control will be achieved by careful design of the communication zone, but to be flexible it is required to change the geometry with each change of operating conditions.

The problem is even more complicated, since the existence of a gas bypass, in the same direction as the circulation, has been found by almost all the authors (Yang and Keairns, 1978, 1983; LaNauze and Davidson, 1975; LaNauze, 1976; Hofbauer, 1983, and Kuramoto et al., 1981, 1985). This bypass concerns mainly the communication zone and has been found to depend very much on the geometry of this region (Yang and Keairns, 1978, 1983). The flow in this region thus appears to be very complex. Consequently, most authors tried to correlate the circulation rate of solids to operating variables such as aeration rates or pressure drop across the communication zone (Yang and Keairns, 1978). Unfortunately, such correlations cannot be safely applied to other systems.

This is one of the reasons why Kuramoto et al. recently tried to understand in more detail the circulation of particles (Kuramoto et al., 1986). They used a much simpler system than the four-compartment one, made of only two compartments. These authors found that the circulation rate of solids could be controlled by the aeration rate in the upflowing compartment and by the area of the communication orifice. They developed an equation, based on the analogy of the flow of a liquid through an orifice, which could explain the results obtained with the four-compartment cold model and predict the value of the circulation rate of particles within 40%. Despite the quality of their results, their attempt does not answer some crucial questions:

- Which one of the two mechanisms of control, previously mentioned, is the most efficient?
- What are the laws of variation of the resisting forces with the operating variables?
- What is the link between the particle circulation and the gas bypass?

Therefore, confusion prevails and the above questions must be answered by means of a new approach which will aim at understanding the phenomena. This is the object of this study, which is based on a preliminary rigorous theoretical analysis.

Theoretical Approach

The approach proposed here will follow three major steps:

- Identifying the operating principle of circulating systems from a hydrodynamic point of view, from the analysis of Kunii's four-compartment reactor
- Deriving equations for the driving and resisting forces
- Drawing the consequences for the experimental program

Operating principle of circulating systems

The fact that particles circulate between the four compartments of Kunii's reactor implies that there exists a driving force for the circulation. Since stability of the circulation rate of solids is always observed, it is necessary that a resisting force counterbalances the driving force, so that the whole system is in equilibrium. Finally, the existence of a real operating flexibility means that this equilibrium can be adjusted to specified conditions. In fact, the problem must be solved in terms of forces equilibrium.

In Kunii's system, the reaction (biomass gasification) imposes the following features:

- The fluidization velocity in the two reacting compartments
- The four-section design to allow complete separation of the reacting compartment atmospheres

In fact, these features represent only chemical restraints, and from a hydrodynamic point of view and for a better understanding of the phenomena, the geometry of the circulating system can be greatly simplified to its essential principle, as shown in Figure 1. The two compartments communicate at the bottom of the system through a rectangular orifice of height, H_f, and width, L. The particles flow over a partition plate at the top of the system. Each compartment is aerated independently. In industrial conditions, the value of H_f is determined when designing the reactor and cannot be easily varied for technical reasons. The value of the solids circulation rate is fixed by the reaction itself. Therefore, the only operating variable is the aeration rate in a compartment which is not reacting.

The circulating system is divided into three zones of distinct hydrodynamic behavior:

- Zone I: downward fully developed flow
- Zone II: upward fully developed flow
- Zone III: communication zone, horizontal flow

The forces exerted on the gas-solids suspension will be calculated in these three zones.

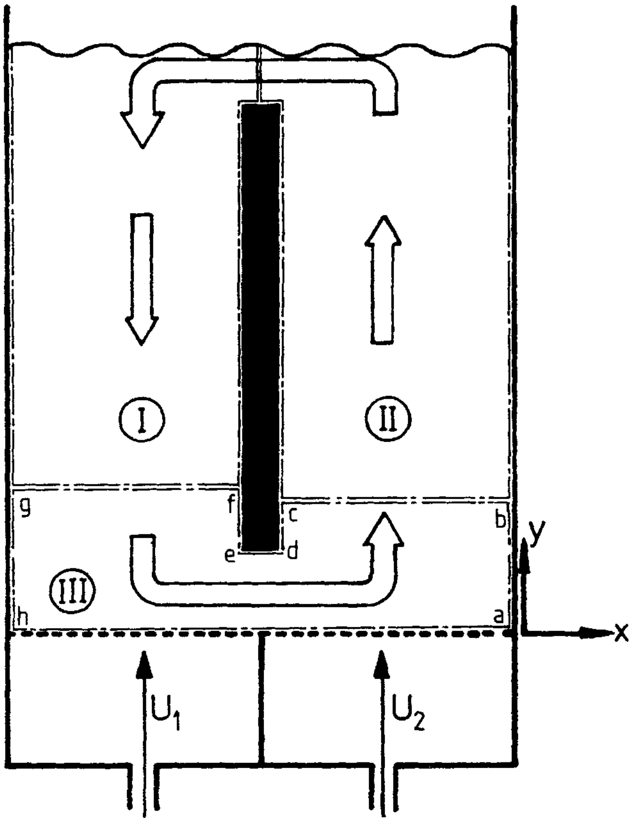

Figure 1. Simplified system of circulation

Equations for forces

Steady-state conditions are assumed. The theoretical approach adopted here follows from an analysis developed by Molodtsof (1985) and is based on the general probabilistic multiphase flow equations (Molodtsof, 1985; Molodtsof and Muzyka, 1989). The rigorous development of the equations presented here can be found in Fox (1987). The validity of the theoretical picture of the flow as represented in Figure 1 (i.e., a communication zone surmounted by two regions of vertical fully developed flow) has been confirmed throughout the experimental work.

In the vertical flowing regions, the flow is fully developed. Therefore, the balance of forces calculated in the zones I and II, written on axis Oy, reduces to

$$\frac{\Delta p^{I}}{L} = (\rho_s - \rho)(1 - \epsilon^{I})g - F_w^{I} \quad (zone\ \mathrm{I}) \tag{1}$$

$$\frac{\Delta p^{II}}{L} = (\rho_s - \rho)(1 - \epsilon^{II})g - F_w^{II} \quad (zone\ \mathrm{II}) \tag{2}$$

since the inertial forces are equal to zero. The term in the left-hand side of Eqs. 1 and 2 is the pressure gradient, as measured with manometers. The first term of the righthand side is the apparent weight of the solids. The second term represents the overall resisting force exerted on the solids. It accounts for the forces linked by intergranular stresses and exerted by the walls and surrounding particles. This is a force per unit volume and it is positive when directed upwards. The two forces can be readily calculated, provided that the pressure gradients and the porosities, ϵ^{I} and ϵ^{II}, in zones I and II are known. The terms, ρ_s and ρ, represent the density of the particles and of the gas, respectively; g is the acceleration of gravity.

The same procedure is applied to the communication zone. This time, the force balance is written on axis Ox:

$$\int_{hg \cup dc} Lp\,dx - \int_{ef \cup ab} Lp\,dx + F_f = 0 \tag{3}$$

The first two terms of Eq. 3 represent the driving force of the circulation. It is equal to the difference between the integral of the pressure profiles on faces *hg* and *dc* and on faces *ef* and *ab* (see Figure 1). It is noteworthy that this is a true force (unit = Newton) and not a pressure difference as has been assumed in the past to define the driving force of the flow. The third term equals the overall resisting force in the communication zone, due to the friction of particles on the walls in this region (including the grid). Equation 3 expresses the equilibrium of the driving and resisting forces in the communication zone. Consequently, the resisting force, F_f, can be calculated from the knowledge of the pressure profiles on *all* the rigid faces in this region, through Eq. 3.

Consequences for the experimental program

It appears from Eqs. 1, 2, and 3 that the driving and resisting forces, involved in the equilibrium of the circulating system of Figure 1, can be readily calculated, provided that the following variables are known:

- The porosities in the two compartments
- The complete pressure fields in the compartments (i.e., on *all* rigid faces, partition plate included)

The first ones will be obtained from the expansion curve of the particles, measured during preliminary test series on a simple fluidized bed, using the actual gas velocity (calculated by the law of composition of velocities), since the particles are moving. The pressure fields will be simply measured by means of pressure taps and water manometers. In order to ensure sufficient accuracy in the calculation of forces, the number of pressure taps will be as great as possible.

In all the previous studies published to date, the experiments have been made with a closed-loop circulation system. The results of such a method are series of operating points typical of a given experimental system. No further information on the driving and resisting forces (such as their laws of variation with the operating variables) can be obtained. This is due mainly to the fact that the only way of varying the circulation rate of solids (and thus the equilibrium between these forces) is the modification of the aeration rates in the compartments. Consequently, before examining a possible systematic experimental program, it is necessary to define a proper experimental technique, which will give the laws of variation of the forces and not only global terms, in which the separate effects of W_s, U_1, and U_2 are mixed in an unknown way. The objective of this technique is therefore to make the forces vary independently with W_s, U_1, and U_2, and to separate the resisting forces from the driving force. This has been achieved by means of a new experimental procedure. In this procedure, the two compartments are completely separated by the partition plate. The circulation rate of solids is continuously fed into the downward flowing compartment and is discharged from the upflowing one. This design allows the study, individually, of the influence of W_s, U_1, and U_2 on the forces, and the measure of the circulation rate of solids without disturbing the flow. The resisting forces are then calculated using Eqs. 1, 2, and 3, which are still valid.

Experimental Apparatus

The test apparatus which has been used is shown schematically in Figure 2. The fluidized compartments (5) are delimited by Plexiglass plates fixed on an iron frame, and their section is square ($0.3 \times 0.3\ m^2$). The compartments are completely separated by the sliding Plexiglass partition plate (4). The position of this plate (thus the value of H_f) can be accurately adjusted by means of (3). The disengaging chamber (8) prevents excessive entrainment of particles. The wind box (11) is also separated into two individual boxes to ensure separate and independent aeration of the compartments. The distributors are made of porous sintered brass plates.

The particles are fed into the downflowing compartment from the feeding hopper (1). The solids rate is adjusted with a valve (2) and can be stopped by a pneumatic valve (2bis). After changing of direction under the edge of the partition plate, the particles enter the upflowing compartment and overflow into the discharge system (7). At this stage, the solids can either be recycled to the feeding hopper through the elevator (10), or sent to the solids rate measurement system (9) through the flow deviating system (6).

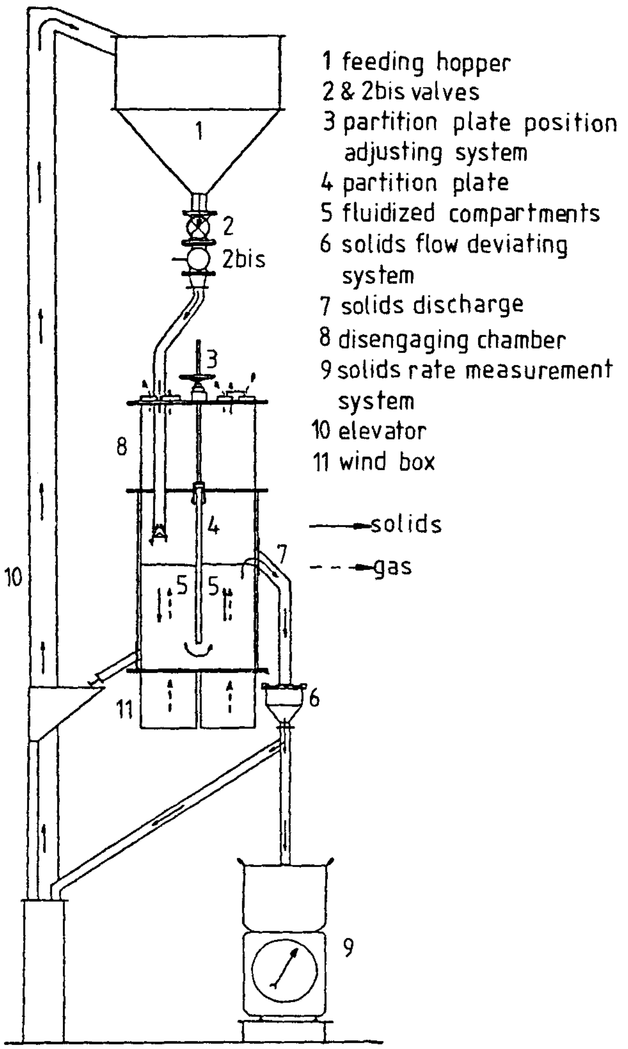

Figure 2. Experimental apparatus.

The partition plate is equipped with 16 pressure taps on each face in order to verify the hypothesis of the existence of fully developed flow in zones I and II. The number of pressure taps on the lateral plates (facing the partition plate) are 23 and 20 for compartments 1 and 2, respectively.

The solids rate is obtained by dividing the measured weight of particles by the time necessary to fill the bucket (see Figure 2). This measurement has been made twice for each test. The aeration rates in the compartments are measured by normalized orifice meters. The fluidization gas is air. Particles of sand (mean weight diameter = 210 μm) were used throughout the experiments, their minimum fluidizing velocity being 4.3 cm/s. Details of the design of the experimental apparatus can be found in Fox (1987).

Experimental Results

The test series were not organized as a conventional parametric study. In fact, the objectives of the experiments were to find the best operating conditions (i.e., most important regulating effect) and to study the variation of the resisting forces with the operating variables. Consequently, only two variables were varied systematically: W_s and U_1, during every test series. Several arrangements of values of H_f and U_2 have been tried. The ranges of variation of the operating variables were:

W_s: 0 to 5 ~ 6 t/h (0 to 2 kg/s)

U_1: 3 to 9 cm/s

H_f: 0.5, 1, 5 and 15 cm

U_2: 6, 7, 8 and 9 cm/s

In order to explain the regulation mechanism involved in the control of the solids circulation rate, only a significant sample of the experimental results will be presented here.

Horizontal resisting force

This force, noted F_f, is calculated with Eq. 3 where the integration domain is limited to the region where the pressure profiles are different on either faces of a compartment. The influence of W_s and H_f is represented in Figure 3. The effect of "closing" the orifice (i.e., decrease of H_f) appears very clearly in this figure. When the value of H_f is greater than 5 cm, the horizontal resisting force, F_f, does not exceed 6 to 7 N, the scatter of the data is important, and is of the same order of magnitude as the experimental error. No "real" trend of variation with W_s can be observed in these conditions and therefore, when $H_f > 5$ cm, *the communication zone does not exert a significant resistance to the flow of solids.*

The situation is much different for the data obtained with $H_f = 1$ and 0.5 cm. The values of F_f are quite significant and the variation of this force with W_s and H_f is sharp. The trend of variation appears very clearly, and in these conditions ($H_f \leq 1$ cm), *the communication zone exerts a real resistance to the flow of solids.*

The effect of the gas velocity in the upward flowing compartment, U_2, is also shown in Figure 4. For $H_f = 1$ cm, two curves are obtained for two different values of U_2. This is due to the

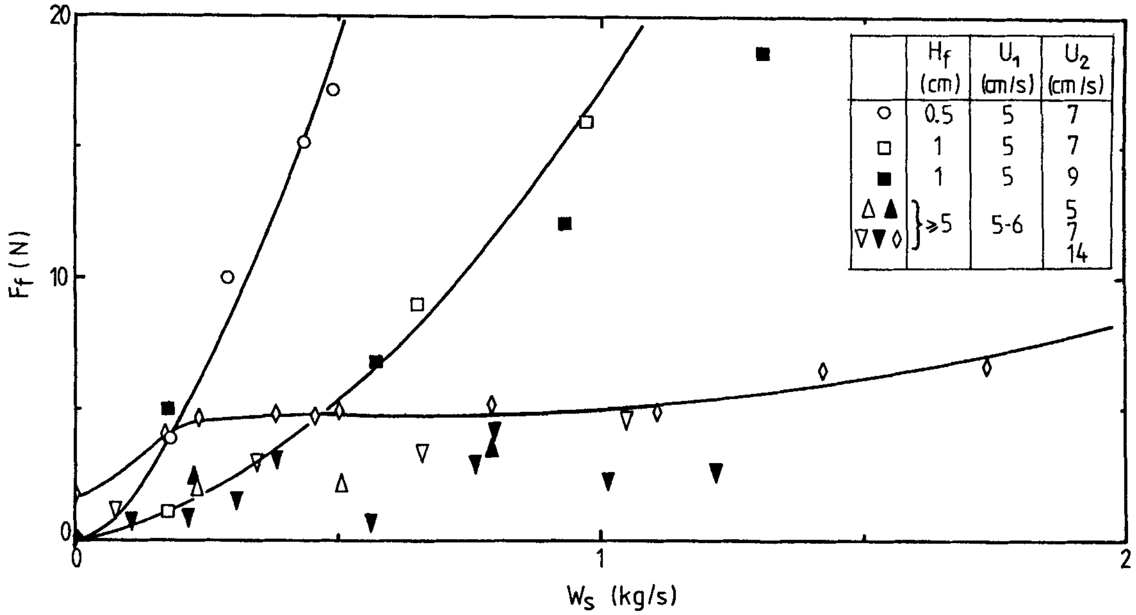

Figure 3. Influence of H_f and solids circulation rate on the horizontal resisting force.

calculation procedure for F_f (see Eq. 3), since the pressure profiles on the rigid faces of the communication zone depend on W_s, U_1, and U_2. The trend of variation is the same in both cases.

These results show that a real effect of regulation of the circulation rate of solids can be obtained by proper arrangement of the geometry of the communication zone (the value of H_f in this study). Unfortunately, the conditions in which the regulation is the most efficient (high values of F_f) might be quite inadequate for industrial purposes, as will be discussed in the next paragraph.

This first remark is confirmed by the influence of the gas velocity in the downflowing compartment, U_1, as shown in Figure 4. It appears that the force, F_f, varies sharply between two horizontal levels, which makes the accurate control of the circulation rate of solids difficult. For these reasons, the phenomena which are responsible for the horizontal resisting force will not be further examined.

Vertical resisting forces

The vertical forces in zones I and II are calculated from Eqs. 1 and 2, with the values of the pressure gradients measured on the lateral plates and of the porosities (determined from the expansion curve of the sand particles), in compartments 1 and 2. This procedure is correct since for all the experiments the pressure profiles on these plates were linear (fully developed flow).

The variation of the vertical force in compartment 1 with U_1 is

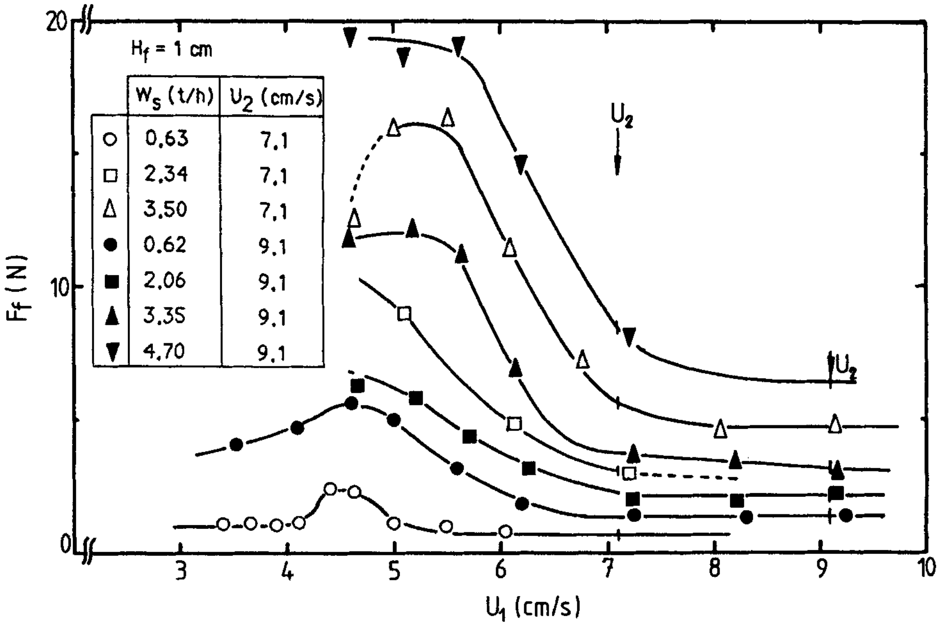

Figure 4. Influence of U_1 on the horizontal resisting force.

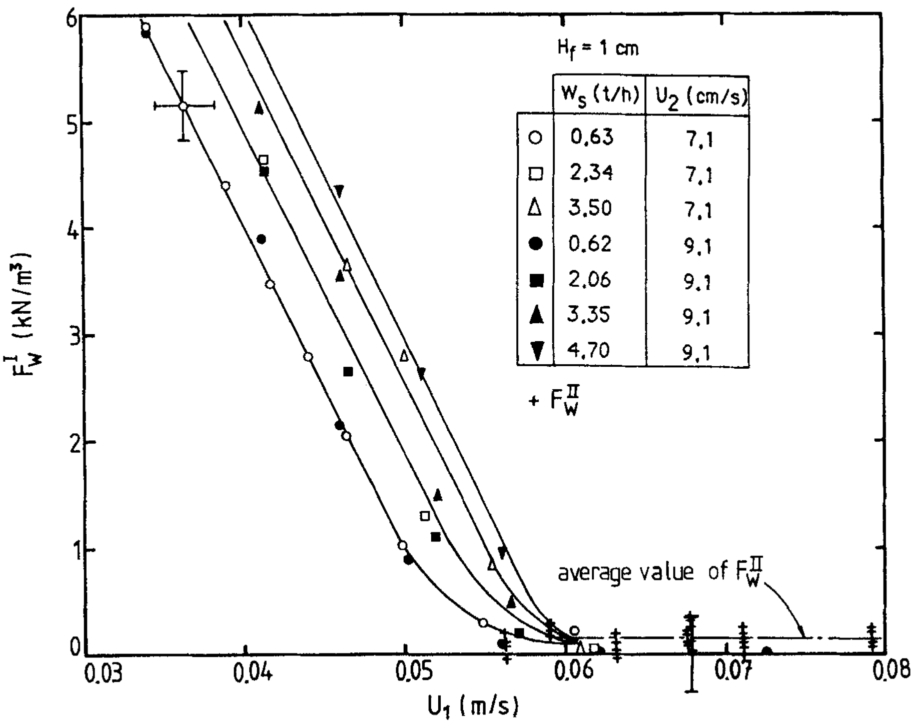

Figure 5. Influence of U_1 and W_s on the vertical resisting forces.

represented in Figure 5, for several values of W_s and U_2. The value of H_f is 1 cm. The values of the vertical force in compartment 2, for *all* the experiments (i.e., all values of H_f), are also shown in Figure 5. A great difference of order of magnitude between these two forces is observed. In fact, F_w^{II} is generally small and close to the value of the experimental error in all cases, as shown by the error bar. Consequently, this force will be neglected in the analysis of the results.

On the other hand, the variation of F_w^I with U_1 is really sharp. Since this force is always positive, it is directed upwards. Therefore, F_w^I is a true resisting force. The values of this force can be very high (about 40% of the apparent weight of solids), which shows its efficiency in the control of the circulation rate of solids. All the curves have a similar trend of variation: a linear part with high negative slope, and a horizontal level. The curves progressively shift to the righthand side as the rate of solids increases. No significant effect of U_2 can be observed. The horizontal level occurs for values of U_1 between 5.5 and 6 cm/s, depending on the value of W_s. Beyond these values of the gas velocity in the downflowing compartment, the resisting force exerted by the walls on the flow, in this region, will be neglected ($F_w^I = 0$), for the same reasons as for F_w^{II}.

The most interesting part of the curves in Figure 5 is the linear one. The vertical force, F_w^I, varies to a great extent in a narrow range of variation of U_1. For the sand particles used in this work, the variation of U_1 ranges from U_{mf} to 1.5 U_{mf}. The results presented in Figure 5 clearly show the existence of a *high* vertical resisting force in the downflowing compartment which can be *easily adjusted*. Consequently, they will be examined in order to identify and understand the phenomena which are responsible for the vertical resisting force, F_w^I. One important feature of the curves in Figure 5 is the slope of their linear part. This slope can be calculated from the experimental data, and is equal to $-3.05 \cdot 10^5$ Pa · s · m^{-2}. This value is very close to the value of the slope of the fluidization curve, $\Delta p/L = f(U)$, determined during the expansion experiments, in the defluidized flow regime, which is about $3 \cdot 10^5$ Pa · s · m^{-2}. The opposite sign is due to the fact that, from Eq. 1, since the porosity is constant in a defluidized flow regime, F_w^I varies like $\Delta p/L$, but with a minus sign. This means that, for any value of the circulation rate of solids, compartment 1 is always defluidized (which has been confirmed by visual observation), even if the superficial velocity, U_1, is greater than the minimum fluidizing velocity, as shown in Figure 5.

The other important feature of these curves is the progressive shift to the right, as W_s increases. In order to explain that shift, the data of Figure 5 have been replotted using a different abscissa:

$$\text{new abscissa} = \frac{U_1}{\epsilon^I} - V_1$$

where V_1 ($V_1 > 0$) is the vertical component of the actual solids velocity, defined as:

$$V_1 = \frac{W_s}{\rho_s A(1 - \epsilon^I)} \tag{4}$$

in which A represents the area of the compartment ($0.3 \times 0.3 = 0.09$ m^2). This new representation is shown in Figure 6. It appears clearly that this procedure results in only one curve, where all the experimental points are together. Actually, this regrouping of data corresponds to a physical phenomenon, which has been mentioned previously: the gas bypasses in the same direction as the circulation itself. The shift to the right-

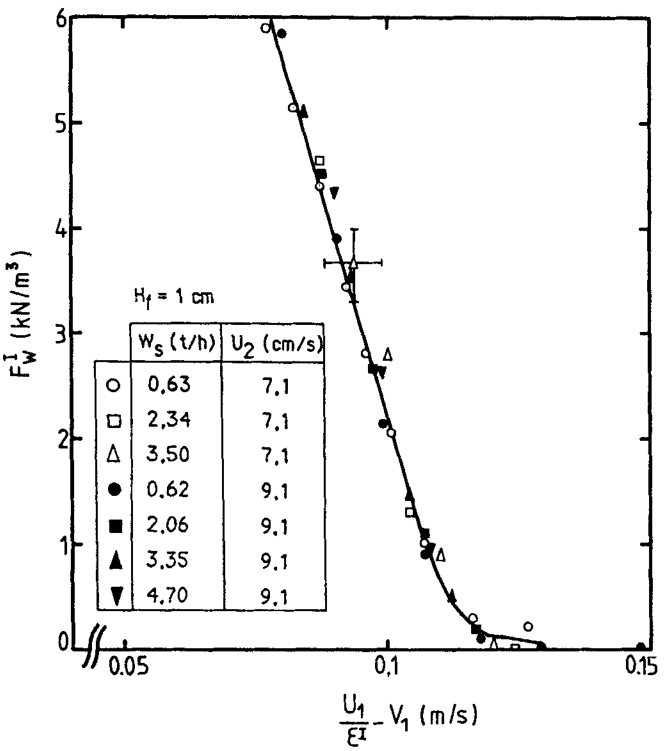

Figure 6. Variation of F_w^1 with the new abscissa.

hand side of the curves in Figure 5, as W_s increases, is due to the increase in the rate of bypassed gas, passing from compartment 1 to compartment 2. The definition of the new abscissa shows that the bypass rate is *about proportional* to the circulation rate of solids, as obtained by Yang and Keairns (1978), and by Hofbauer (1983). From the analysis of the data presented in Figure 5, it is possible to explain in detail the mechanism which is responsible for the variation of the vertical resisting force in compartment 1.

This mechanism is the *progressive defluidization* of compartment 1. In terms of the operating variable, the state of fluidization in this region depends on the aeration rate (i.e., U_1) and on the circulation rate of solids, W_s. The superficial gas velocity, U_1 is *the direct control variable* of the vertical resisting force in compartment 1, as is shown in Figure 5. But on this effect of the aeration is superimposed the effect of the circulating movement of particles itself. It appears that as circulation is initiated, compartment 1 becomes more defluidized, because of the gas bypass from compartment 1 to compartment 2. The defluidized state in this region increases with the circulation rate of solids. From the point of view of the understanding of the phenomena, the major consequence of the mechanism explained here is that the accurate control of the circulation rate must be achieved *not with the help* of the bypass, but *in spite of* the bypass of gas.

Design and Operation of Circulating Systems

The experimental results presented here show that the control of a circulating system depends on three major phenomena:

- The resistance in the communication zone
- The vertical resistance in the downflowing compartment
- The gas bypass between the compartments

Figures 3 and 4 show that the mechanisms responsible for the horizontal resisting force, F_f, are rather complex and difficult to understand fully, even though their nature is known (wall/particles friction). From an industrial point of view this might be the less important consequence. In fact, the conditions under which this force efficiently controls the rate of solids are of great significance. It appears that efficient control of W_s can be achieved only for very *narrow* orifices (see Figure 3). Industrial operating conditions prevent the use of such orifices, because of the possible agglomeration of particles followed by clogging up of the orifice. It is clear that a small variation of the orifice opening is accompanied by a sharp variation of F_f. Consequently, during operation at high temperature, the value of the horizontal force will vary to a great extent, since effects of metal expansion are likely to occur. Finally, in order to ensure a real flexibility, in terms of W_s, the opening should be variable. This means that moving plates should be used inside the circulating system, which is almost impossible for technical reasons (high temperature, corrosion, erosion, etc.). Therefore, the communication zone does not provide a proper method of controlling the circulation rate of solids, since stability and flexibility of this rate cannot be ensured, as the value of F_f cannot be directly controlled. This region only gives rise to self-regulation and ensures the intrinsic stability of the system, preventing any eventual divergence.

Fortunately, the second resisting force appears to be the ideal way of controlling the circulation rate of solids. The value of this vertical force can be very high and it is variable to a great extent with the operating conditions. Moreover, this force can be easily controlled by the proper adjustment of the aeration rate in the downflowing compartment. From what has been said so far, it appears that the design and the operation of circulating systems must be examined in terms of the control of the vertical resisting force and the consequences which follow from it.

Since the value of F_w^1 (and thus the circulation and operation of the whole reactor) is controlled by the aeration rate of one compartment, this rate must be *totally* adjustable. Consequently, it is out of the question to regulate a gasification reactor, for example, by means of the aeration of a reacting compartment. Thus, the only possible geometry is the one invented by Kunii: the four-compartment reactor (two reacting compartments and two inert transfer compartments). In such a design, the circulation rate of solids is directly controlled by the aeration rates in the inert compartments. The gas velocity in the other compartment is fixed by the chemical reaction itself. Therefore, the control of the value of F_w^1 represents a hydrodynamic restraint, which implies a four-compartment design. The chemical restraint is the complete separation of the atmospheres of the two reacting compartments.

In order to achieve an efficient control of the circulation, the inert compartment(s) must be maintained in a defluidized state (between U_{mf} and 1.5 U_{mf} for this sand). It is noteworthy that in almost all the studies published to date, at least one compartment was operated in a defluidized state (Yang and Keairns, 1978; LaNauze, 1976; Hofbauer, 1983, and Kuramoto et al., 1986). This shows that the authors found, more or less empirically, the most favorable conditions for the efficient regulation of their system.

It appeared that the circulation rate of solids can be efficiently controlled by proper adjustment of the aeration rate in the inert compartment(s). In fact, in closed-loop operation (that is typical industrial conditions), the problem is not only circulation control, but rather, process piloting. This means that, as a first step, a relevant variable, which is typical of the proper operating conditions and of the value of W_s must be measured in the reacting compartment(s) and, as a second step, that the aeration rate of the inert compartment(s) is set and adjusted, according to the value of this measured variable. For instance, Yang and Keairns (1974) tried to control the circulation through the value of the pressure difference between the draft-tube and the downcoming annulus of their system, but this type of variable is not necessarily typical of the proper operating conditions. As an example, for a gasification reactor, this variable could be the temperature in one reacting compartment, since the value of the circulation rate of solids is fixed by the thermal equilibrium between the two reacting compartments. The measurement of this temperature will give the relevant information, if malfunctioning occurs. This malfunctioning can be corrected by proper opening or closing of the control valve of the aeration in the inert compartments, controlled by the thermocouple. Such a regulation system does not reduce the operating range of the reactor, since the value of W_s can be totally adjusted by the control of the aeration rates in the inert compartments.

Although this aeration control is easy to achieve, it must be carried out very accurately. The slope of the linear part of the curves in Figure 3 shows that for a small variation of U_1, the value of F_w^I changes drastically. The operating conditions in the inert compartments could therefore change to a great extent. Thus, the accuracy of the aeration rate control must be maximum. This requirement can become very severe, but it can be technically achieved in two ways. First, very accurate measuring and controlling devices can be used, even if the economical investment is high. Second, if accurate control of large aeration rates is difficult to achieve, small rates are much simpler to adjust very accurately. Therefore, the horizontal area of the inert compartment(s) can be reduced in order to considerably decrease the value of the aeration rate to be controlled, keeping the gas velocity equal. This can be achieved easily since strict symmetry of the compartments is not required by the process itself. In our own system, the inert compartments are of an industrial size, but in industrial operations, the reacting compartments could be much bigger. In any case, the values of the rates to be controlled remain quite small, since the inert compartments are always defluidized.

The gas bypass between the compartments appears to be initiated by the circulation of particles, and it seems proportional to the circulating rate of solids. Therefore, *it is impossible to prevent this bypass phenomenon,* and the control of the circulating system must be achieved in spite of it. Firstly, since the bypass contributes to maintaining the defluidization of the downflowing compartment, it is essential to know, even approximately, the way in which the rate of bypass varies with the operating conditions. This can be achieved by measurement of pressure field measurements (Fox, 1987). Attention must be paid to the design of the orifice, due to its great effect on the bypass characteristics (Yang and Keairns, 1978, 1983). Therefore, the orifice must be of a simple geometry, in order to make the study of the bypass phenomenon as simple as possible. This argument confirms the fact that the design of the communication zone should be kept simple, so as to make the local phenomena (friction and bypass) simpler. The term "design of the communication zone" includes the aeration system (grid, gas injection system, . . .) as well as the geometry of the orifice.

Finally, since the gas bypass cannot be prevented, it is advisable that the inert compartment(s) should be aerated with a gas which is inert for the chemical reaction to be used. Again, knowledge of the bypass characteristics is of prime importance, since this phenomenon causes the mixing of the reacting gas with the bypassed gas, in the reacting compartment(s), which must be taken into account.

Conclusion

The circulation of particles between two fluidized beds has been studied by means of an open-loop circulating apparatus made of two compartments totally separated by a partition plate, in order to make the driving and the resisting forces acting on the flow vary separately with the circulation rate of solids and the aeration rates in the compartments. The problem has been examined in terms of an equilibrium between the driving and resisting forces. Equations have been developed to calculate these forces from measured quantities such as pressure gradients and porosities in the compartments. The experimental results have shown that the most efficient way to control the circulation rate of solids is by varying the value of the vertical resisting force in the downflowing compartment by adjusting the state of defluidization in this region. The horizontal resisting force appeared to be very small, in industrial operating conditions. The existence of a gas bypass between the two compartments has been confirmed and its link with the circulation of solids has been explained.

In industrial operating conditions, an accurate control of the circulation rate of solids can be achieved by proper adjustment of the gas rate fed into the downflowing compartment, within a range close to the minimum fluidizing rate.

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Notation

A = area of compartments, 0.09 m^2
F_f = horizontal resisting force in communication zone, N
F_w^I, F_w^{II} = vertical resisting force (per unit volume) in compartments 1 and 2, N/m^3
g = gravity acceleration component, m/s^2
H_f = height of orifice, m
L = width of orifice, m
p = pressure, Pa
U_{mf} = minimum gas fluidizing velocity, m/s
U_1, U_2 = superficial gas velocity in compartments 1 and 2, m/s
V_1 = vertical component of solids velocity in compartment 1, m/s
W_s = circulation rate of solids, kg/s
x, y = spatial coordinates

Greek letters

$\Delta p/L$ = pressure gradient (Pa/m)
ϵ = porosity
ρ = gas density, kg/m^3
ρ_s = particle density, kg/m^3

Subscripts, superscripts

1, 2 = compartment 1, 2
I, II = zones I and II (Figure 1)
hg, dc, ef, ab = height of wall faces in communication zone (Figure 1)

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