Development of Circulating Fluidized Bed Adsorber

A new fluidized bed which is divided in a looplike shape by a partition wall has been developed for recovering trace elements from a large quantity of industrial water. The bed, a circulating fluidized bed applicable to a liquid-solid two-phase flow, is called a circulating fluidized bed adsorber (CFBA). Adsorbent particles are mixed and carried along with water in the CFBA. At the upper part of the bed, the adsorbent particles are separated from the water flow and recycled in the bed; the depleted water flows out of a water outlet. The CFBA is operated at two to three times higher velocity than conventional liquid-solid contacting systems. The pressure drop in the CFBA is in proportion to the amount of adsorbent suspended in the contacting section. Characteristics of the CFBA, including design considerations, are described.

Susumu Nakamura
Shigeharu Yoshimuta
Masataka Shirakashi
Masayoshi Kanno
Yoshiro Ito
Department of Mechanical Engineering
Faculty of Engineering
Nagaoka University of Technology
Nagaoka, Niigata 940-21, Japan

Introduction

Interest in the recovery of trace elements or removal of trace contaminants from a large quantity of industrial water has increased in recent years, due to concerns about recycling limited resources and environmental protection. Several processes are available for the treatment of the water with relatively low levels of concentration. The adsorption process is considered to be a practical method because of its high selectively, ease of handling, and safety to the environment. However, to recover some amount of the elements by the adsorption process, a huge quantity of water must be contacted with the adsorbent. The most important factor in the treatment of industrial water is therefore a contacting system. The recovery of uranium from seawater is one of these subjects and has been studied for two decades (Kanno, 1984).

In our previous study (Nakamura et al., 1987), a cost estimation on a fixed-bed system for recovering uranium from seawater was conducted. An enormous quantity of seawater must be processed in the adsorption plant for the recovery of uranium, too, since the concentration of uranium in seawater is extremely low: 3.3 ppb (Kanno, 1981). The results have indicated that the major part of uranium production cost stems from the construction of an adsorption plant. The contacting system must therefore be operated at a high linear velocity of water to decrease the adsorption bed area and the uranium production cost.

The linear velocity of water used in conventional adsorption systems for recovery of uranium from seawater—the fixed-bed system and the fluidized-bed system—is limited to about 1 cm/s. The reason is that higher water velocity causes clogging and an increase of pressure drop in a fixed-bed system, and carryover of adsorbent particles in a fluidized-bed system. The velocity limit of 1 cm/s corresponds to one-third to one-fifth of the sinking velocity of an inorganic adsorbent particle. For this reason, an adsorption plant using such contacting systems needs a large bed area and will not be economical.

Koske and Ohlrogge (1982, 1983) proposed the adsorbent loop concept, which was regarded as a contacting system intermediate between the fluidized-bed and slurry systems. They have reported that the loop unit can be operated at a ten times higher velocity than that of a fluidized bed and the adsorption bed area can be significantly decreased. But their results on the design of the loop unit and operating conditions have not been described in detail.

We made a unit based on the adsorbent loop concept and tested it. Among the results, it was clear that the adsorbent particles did not circulate stably in the unit. We have made an effort to overcome the deficiencies of the loop concept, and have constructed a new type of fluidized-bed adsorber, a circulating fluidized bed adsorber (CFBA).

Circulating fluidized beds (CFB) have been used frequently in combustion technology. Two columns, a riser and a downcomer, are the main constituents of the common CFB boiler.

Correspondence concerning this paper should be addressed to Y. Ito.
S. Yoshimuta is currently with Nuclear Fuel Industries, Ltd.

Particles of solid fuels and additives are fluidized by air and burned in the riser. Then, part of the burned particles are carried over from the riser, collected into the downcomer and fed again to the riser. The fluid is air, which is supplied to both the riser and the downcomer to achieve the fluidization of solid particles. Separation of the fluid and solid are carried out by a cyclone separator. The hydrodynamics, heat transfer, and instrumentation of the CFB are of current intensive research interest in chemical engineering (SCEJ, 1988). Most of the studies in this area, as far as we know, have dealt with gas–solid two-phase flow.

The CFBA described in this paper operates with a liquid–solid two-phase mixture and works as an adsorption device. Separation of adsorbent particles and water is achieved without any special separator.

The requirements imposed on the development of the CFBA are:

1. Operation at higher water velocity than fixed beds or fluidized beds
2. Operation at a wide range of velocities
3. The possibility of packing a larger amount of adsorbent

The development and essential characteristics of a CFBA that satisfies above requirements are described in the present paper. The influences of the design of the bed and the properties of adsorbent particles on the fluidized state are also discussed.

Experimental Method

Apparatus

The experimental apparatus is shown in Figure 1. Water was pumped up (maximum 6 L/s) from a pool under the floor into a water tank (500 × 250 × 1,600 mm) made of transparent acrylic plate 10 mm thick. A bed made of transparent polyvinyl chloride plate 5 mm thick was set at the middle of the water tank. The driving force of the water flow into the bed was caused by the difference in water head between the front and the rear of the bed. The water flow rate in the bed was measured by an electromagnetic flowmeter. The flow pattern of water and particles in the bed was measured by an electromagnetic current meter which could measure the two direction components of the velocity vector simultaneously. The movement of particles in the bed was recorded by a video camera and was also observed visually.

Adsorbent

Hydrous titanium oxide granulated with polyacrylonitrile (PAN-HTO) was used as an adsorbent (Nakamura et al., 1988). This adsorbent is considered to be a practical adsorbent for uranium in seawater (Kanno, 1984). The particle size of the PAN-HTO adsorbent had a wide distribution, so it was classified into three classes of mesh, 32/42, 24/32, and 14/24. The average particle sizes, densities, and sinking velocities are listed in Table 1. The average particle sizes were computed from measurements conducted on 150 particles of each class of mesh. The true densities, ρ_t, were determined by the displacement of water with a picnometer. The sinking velocities, u_s, were obtained by dropping individual particles into stagnant water in the column and timing their fall through a 50 cm distance.

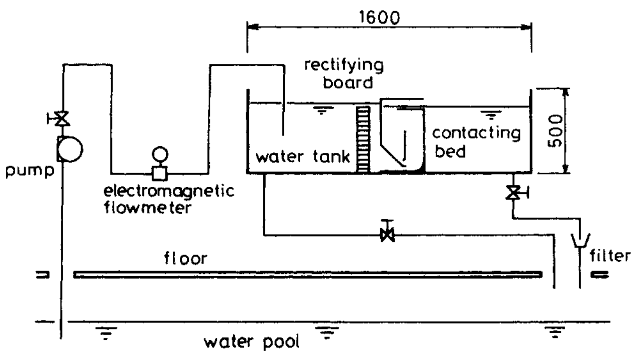

Figure 1. Experimental apparatus.

Development of the CFBA

Test of loop unit

Koske and Ohlrogge (1983) have reported that the adsorbent loop concept enables units to operate at considerably higher velocity. We made a unit based on the adsorbent loop concept and observed the fluidized behavior of the adsorbent in the unit. 14/24 mesh adsorbent was used in the experiment. In our experiment, the adsorbent particles deposited at the bottom of the unit at low velocity were carried over from the unit at high velocity. They did not circulate in the unit without deposit or carryover. Koske and Ohlrogge have reported that the adsorbent particles are separated from the horizontal water flow by gravity and suction in the upper part of the unit, but these failed to work well in our experiment. Furthermore, some of the water flowed into the sedimentation cone where the adsorbent particles separated from the water flow was collected. As a result, turbulence in the sedimentation cone disturbed the sinking of the adsorbent particles.

The deficiencies of the examined loop unit are summarized as follows:

1. There is no velocity range at which the adsorbent particles circulate in the unit without deposit or carryover.
2. Some of the water flows into the sedimentation cone.
3. Separation between water and particles by gravity and suction fails to work well.

In spite of these deficiencies, this type of contacting unit would be a possible alternative to common fluidized beds in obtaining higher water velocity. However, in an effort to overcome these deficiencies, we have developed a circulating fluidized bed adsorber (CFBA) as described below.

Examples of the CFBA

Typical examples of beds examined in the course of the development of the CFBA are shown in Figure 2. The bed shown in Figure 2a is one of the earlier types. In this bed, the bed width is enlarged to help sedimentation of the adsorbent particles at the top of the bed. The bed is essentially made up of the

Table 1. Properties of PAN-HTO Adsorbent

Mesh	d_p mm	ρ_a, g/cm^3 Dry	Wet	ρ_t g/cm^3	ϵ_p	u_s cm/s
32/42	0.51	0.58	1.36	2.77	0.79	1.5–2.4
24/32	0.73	0.58	1.35	2.75	0.79	1.9–3.6
14/24	0.91	0.54	1.35	2.70	0.80	2.7–5.4
Unclassified	0.62	0.57	1.35	2.76	0.79	1.4–4.8

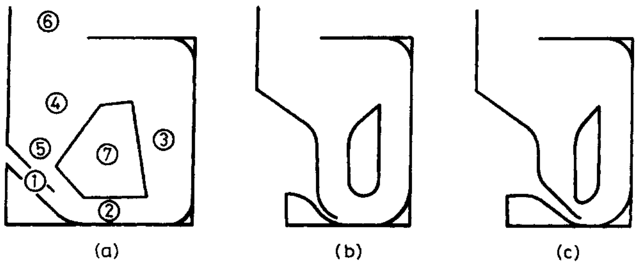

Figure 2. Examples of circulating fluidized bed adsorber.

(a) Earlier type: bed width enlarged to help sedimentation of adsorbent particles at top of bed
1. water inlet; 2. mixing section; 3. contacting section; 4. sedimentation section; 5. packing section; 6. water outlet; 7. partition wall
(b) Middle type: width of bed bottom made narrower than bed top
(c) Prototype of CFBA: width of channel from packing to mixing section is narrowed; packing section works like a hopper

following sections:
(*1*) water inlet
(*2*) mixing section
(*3*) contacting section
(*4*) sedimentation section
(*5*) packing section
(*6*) water outlet
(*7*) partition wall

The behavior of particles at various water velocities revealed the following features of the bed. Deposit of the adsorbent occurred at the corner leading from the mixing to the contacting section, that is, between (*2*) and (*3*) in Figure 2a. It decreased with the increase in the water flow rate, but the adsorbent particles began to carry over before the adsorbent particles deposited were completely suspended. The amount of the adsorbent deposited at the bottom increased with the increase in bed width. It was obvious that the velocities in the water inlet and the mixing section must be increased without an increase in the velocities in the contacting and the sedimentation sections in order to suspend the adsorbent completely.

In the bed shown in Figure 2b, therefore, the width of the bottom of the bed was made narrower than the top of the bed. Furthermore, a water inlet shaped like a nozzle was set near the corner between the mixing and the contacting sections. In this bed, the supplied water mixed with the adsorbent particles falling from the packing section, then the water–particle mixture ascended the contacting section immediately. As the mixture was not transported horizontally at the bottom of the bed, deposit of the adsorbent was avoided. Direct backward flow of the supplied water into the packing section, however, occurred in the bed and the sinking of the adsorbent particles was disturbed. This was because the width of the channel from the packing to the mixing section was relatively large.

In the bed shown in Figure 2c, the width of the channel from the packing to the mixing section was narrowed. Hence a certain amount of the adsorbent was always packed in the packing section, so backward flow was prevented. The packing section works like a hopper. The adsorbent circulated smoothly in this bed without any deposit or a backward flow into the packing section. This bed is a prototype of the CFBA. The final design of the CFBA is shown in Figure 3. The thickness of the bed, T, was kept constant at 65 mm throughout the experiments. Comb-type baffle plates installed in the upper part of the packing section were meant to help the separation between the water flow and the adsorbent. Its effect is described later.

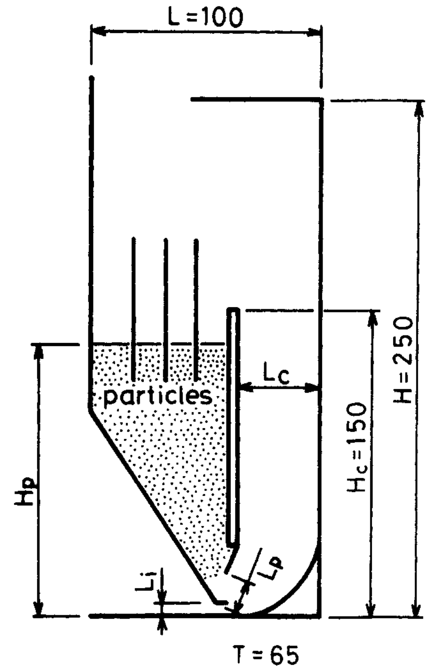

Figure 3. Side view of circulating fluidized bed adsorber.

The features of the CFBA are summarized as follows:

1. A water inlet shaped like a nozzle is set at the bottom near the corner between the mixing and the contacting sections to prevent deposit of the adsorbent.
2. A certain amount of the adsorbent is packed in the packing section to prevent backward flow.
3. Comb-type baffle plates are installed in the upper part of the packing section to help the separation between water flow and the adsorbent.

Characteristics of the CFBA

Flow pattern in the sedimentation section

The velocity vectors of water and particles in the bed were measured at rectangular lattice points under various conditions. The sensor head of an electromagnetic current meter was inserted through the hole drilled at each lattice point on the side wall of the bed. The head was set to measure horizontal and vertical components of the water velocity vector. The two outputs of the meter were recorded by a pen recorder. Typical results are shown in Figure 4. The water velocity in the contacting section, u_c, was kept to 5 cm/s and 14/24 mesh adsorbent was used. u_c was derived by dividing the water flow rate, Q, by the contacting section area, A_c. The water flow in the bed differed in its pattern depending on whether there was any packed adsorbent or not.

When no adsorbent was packed, the water flow ascended the contacting section to the top of the bed. Then it was diverted horizontally and flowed out the water outlet. The direction of the flow in the sedimentation section was counterclockwise. This flow line is represented in Figure 4a.

When a certain amount of the adsorbent was packed, the water flow changed as shown in Figure 4b. The water–particle

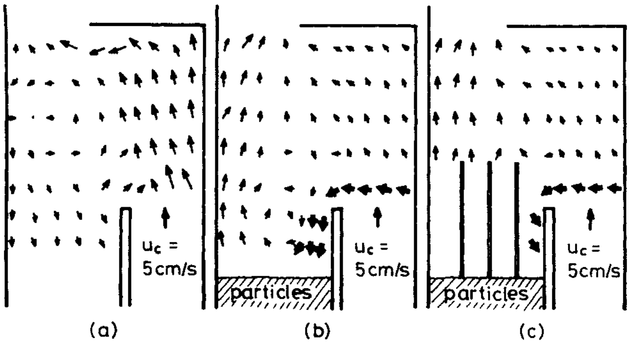

Figure 4. Flow patterns of water and particles in sedimentation section.

(a) No adsorbent packed in bed
(b) A certain amount of adsorbent packed in bed
(c) A certain amount of adsorbent is packed and comb-type baffle plates installed in bed
Thin arrows: velocity vector of water; bold arrows: velocity vector of water–particle mixture
Arrow length corresponds to magnitude of velocity

mixture ascending the contacting section changed its direction downward at the top of the partition wall. Then the mixture flowed into the packing section along the partition wall without separation of water flow and the adsorbent particles. The water–particle mixture behaved like a density current. The direction of the flow in the sedimentation section changed to clockwise.

Separation mechanism of water and particles

In the upper part of the packing section, the water–particle mixture collides with the surface of the packed adsorbent. Then, the particles deposit on the surface and gradually move downward, while the depleted water ascends along the wall and flows out the water outlet. This process is the separation mechanism between the water and the adsorbent particles in the CFBA. This is quiet different from that in the loop unit or in the cyclone separator.

Effectiveness of the comb-type baffle plates

Even though the separation mechanism between the water and the adsorbent particles works fairly well, the velocity range at which the adsorbent particles circulate smoothly in the bed is relatively small. The depleted water flow from the packing section to the water outlet is not uniform, as shown in Figure 4b. It has a fast component near the wall. This fast stream is the cause of the carryover at a relatively low velocity. In order to disperse the fast flow into a uniform slower flow, baffles were installed in the upper part of the packing section. The baffles consist of three comb-type plates. Each plate has slits of 5 mm pitch. The fast water flow in the sedimentation section was dispersed successfully and made uniform by the baffle plates, as shown in Figure 4c. As a result, the velocity range at which the adsorbent particles circulate smoothly in the bed was considerably extended.

We obtained the desired fluidized state; the adsorbent particles circulate well in the bed without deposit or carryover. This state, the circulating fluidized state, is realized in a certain region of the water velocity which will be referred to as the circulating fluidized region.

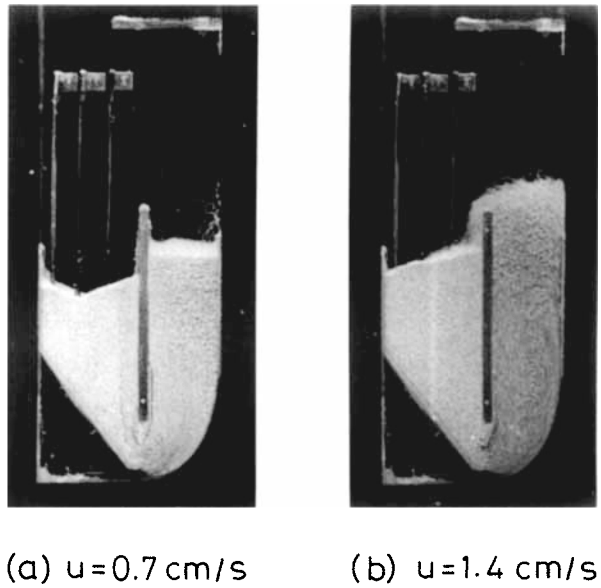

Figure 5. Circulating fluidized bed adsorber during operation.

(a) Early state of operation: water–particle mixture does not ascend up to top of partition wall
(b) Operation in circulating fluidized state: adsorbent particles circulate smoothly in bed

Photographs of the CFBA during operation are displayed in Figure 5. The adsorbent is PAN-HOT of 14/24 mesh. The CFBA is operated at a mean linear velocity of 0.7 cm/s in Figure 5a. The water velocity in the contacting section is calculated as the mean linear velocity times 2.5. In the case of Figure 5a, the water–particle mixture does not ascend to the top of partition wall. Deposit of the adsorbent and the backward flow are observed. In Figure 5b, however, the CFBA is operated at a mean linear velocity of 1.4 cm/s and the adsorbent particles circulate smoothly in the bed without deposit or carryover. The difference in water head between the front and the rear of the bed, which is the driving force of the water flow into the bed, was about 2 cm.

Relationship between amount of packed adsorbent and circulating fluidized state

The amount of packed adsorbent is one of the important factors for operating the bed. It has a great influence on the adsorption efficiency. The relationship between the amount of packed adsorbent and circulating fluidized state was examined.

The results are shown in Figure 6. The packing ratio, W, is the ratio of the amount of packed adsorbent to the total bed volume. The packed adsorbent height, H_p, is the adsorbent height measured in the packing section during operation. The circulating start velocity, u_{min}, is the minimum velocity at which the adsorbent particles begin to circulate in the bed without deposit and backward flow. The circulating limit velocity, u_{max}, is the maximum velocity at which the adsorbent particles circulate in the bed without carryover. The adsorbent particles circulate well in the water velocity region of $u_{min} \leq u \leq u_{max}$. This water velocity region, the circulating fluidized region, is suitable for operation of the CFBA.

In Figure 6, α is the volume fraction of the adsorbent particles in the contacting section, that is, the ratio of bulk volume of the

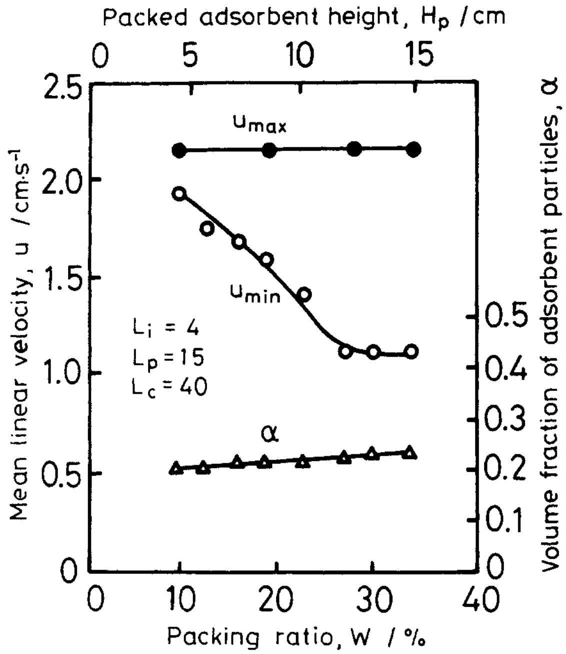

Figure 6. Relationship between amount of packed adsorbent and fluidized state.

u_{min}, circulating start velocity
u_{max}, circulating limit velocity
$u_{min} \leq u \leq u_{max}$, circulating fluidized region
α, volume fraction of adsorbent particles in contacting section

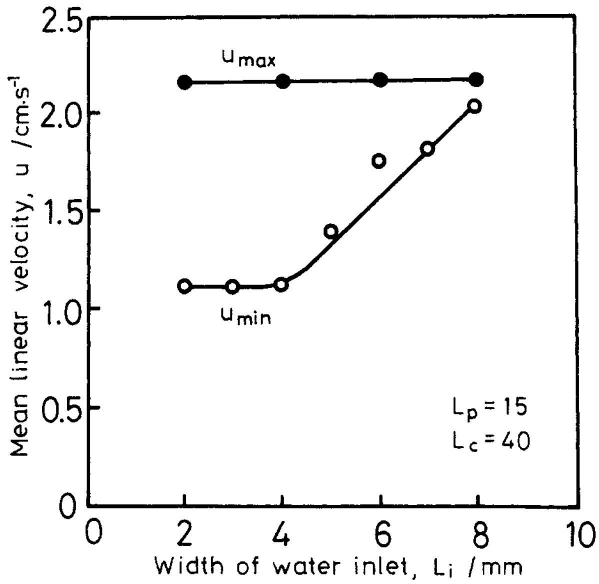

Figure 7. Influence of water inlet width L_i on the circulating fluidized state.

Packing ratio W of adsorbent = 34%

adsorbent suspended in the contacting section to the volume of that section. The value of α increased slightly with the increase in W, but the change was small.

The value of u_{max} was independent of W, while u_{min} decreased with W and reached a minimum at 27%. When W is low (i.e., H_p is low), the flow resistance in the packing section is relatively small and a part of the supplied water flows into the packing section. Hence the water flow rate in the contacting section becomes insufficient to circulate the adsorbent. u_{min} must be increased with the decrease in W for the above reason. When enough of the adsorbent is packed in the bed, the flow resistance in the packing section is large and all of the supplied water flows into the contacting section; the adsorbent begins to circulate in the bed at a lower flow rate than in the case of a low W. Hence u_{min} decreases with the increase in W and the circulating fluidized region is extended.

Design Considerations for the CFBA

The CFBA must obviously be scaled up to use it for recovering trace elements from industrial water in practice. To do so, the influence of each section of the CFBA on the circulating fluidized state should be examined in detail. 14/24 mesh adsorbent was used in experiments to examine the various section influences.

Influence of water inlet width

The deposit of adsorbent at the bottom of the bed is greatly influenced by the water inlet width, L_i. The influence of L_i on the circulating fluidized state is shown in Figure 7.

The value of u_{min} increased with an increase in L_i, but u_{max} was independent of it. Hence the circulating fluidized region narrowed as L_i was increased. When the water flow rate is kept constant and L_i is increased, the water velocity at the water inlet becomes low and the deposit of the adsorbent occurs. Thus u_{min} must be increased with the increase in L_i to prevent a decrease of velocity of entering water and the deposit of the adsorbent. The carryover of the adsorbent particles, however, is influenced by the water velocity at the top of the bed. Hence u_{max} is independent of L_i, while u_{min} increases with the increase in L_i; the circulating fluidized region becomes smaller.

Influence of contacting section width

The influence of the contacting section width, L_c, on the circulating fluidized state is shown in Figure 8. The width L_c was changed by the increase in thickness of the partition wall. The change in u_{min} was little, while u_{max} gradually increased with the increase in L_c. When L_c becomes narrow, the supplied water ascends in the contacting section without slowing down. Thus the water–particle mixture ascends up close to the top of the bed and the adsorbent particles carry over easily. For this reason, u_{max} gradually increases with increase in L_c.

Influence of particle nozzle width

The volume fraction, α, of the adsorbent particles in the contacting section is directly concerned with the adsorption efficiency, since contact between water and adsorbent is conducted mainly in this section. Figure 9 shows the influence of the particle nozzle width, L_p, on α. The value of α increased with the increase in L_p from 0.15 to 0.35. α was also affected by the mean linear velocity of water, but the water velocity influence was small compared with the effect of L_p.

Sinking Velocity of an Adsorbent Particle and the Circulating Fluidized Region

The influence of the physical properties of the PAN-HTO adsorbent on the circulating fluidized state was examined.

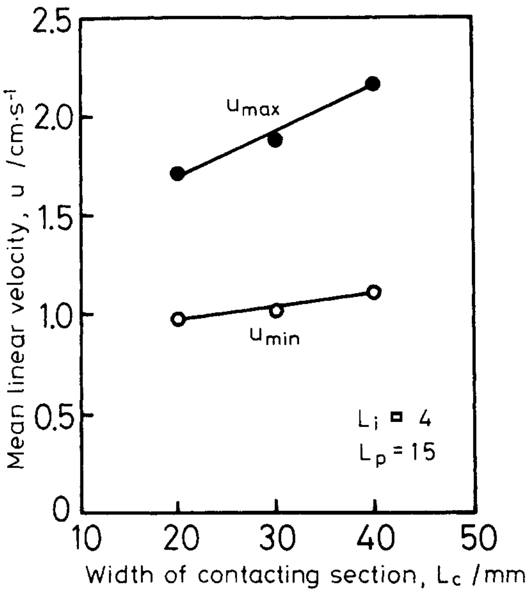

Figure 8. Influence of contacting section width L_c on circulating fluidized state.
$W = 34\%$

Figure 10 shows the relationship between the sinking velocity, u_s, of an adsorbent particle and the circulating fluidized region. Both u_{min} and u_{max} were in proportion to u_s. For adsorbent of 0.91 mm particle size and 4.1 cm/s sinking velocity, the circulating fluidized region ranged from 1.2 to 2.4 cm/s. These velocities correspond to a range of u_c from 3.0 to 6.0 cm/s. A higher velocity than the sinking velocity of the adsorbent is achieved in the contacting section. The line marked ▲ in Figure 10 represents u_{max} measured when the comb-type baffle plates were not installed in the CFBA. It can be seen that the circulating fluidized region is considerably extended by installing the baffle plates.

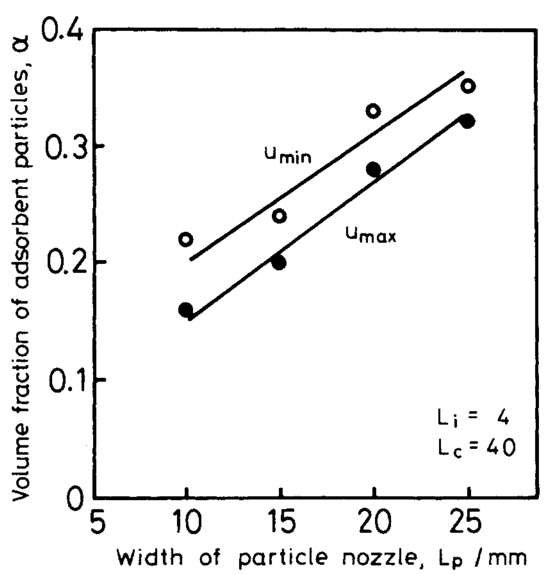

Figure 9. Influence of particle nozzle width L_p on volume fraction α of particles in the contacting section.
$W = 34\%$

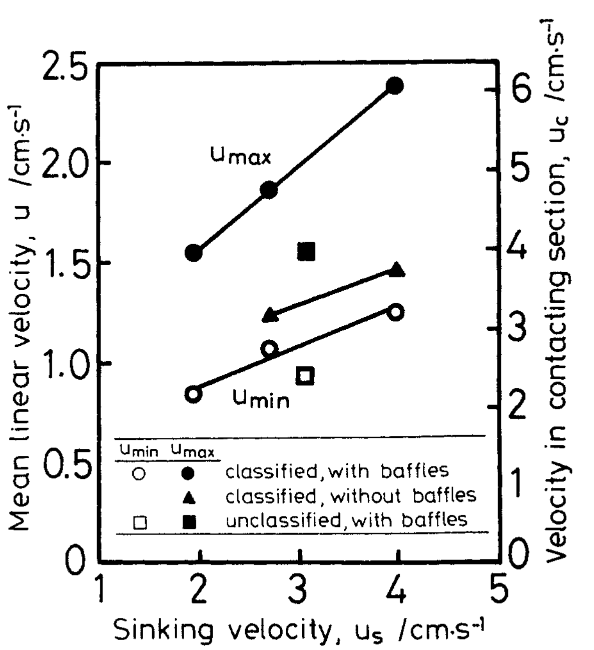

Figure 10. Relationship between sinking velocity of an adsorbent particle and circulating fluidized region.
$W = 34\%$

When the unclassified PAN-HTO adsorbent was used, u_{min} was 0.9 cm/s and u_{max} was 1.5 cm/s. The unclassified adsorbent had some fine particles and these were carried over more easily than the coarse particles. Thus u_{max} was smaller than those of the coarser and classified adsorbents. The velocity range of 0.9 to 1.5 cm/s, however, is two to three times larger than that in the fluidized bed of the Nio Institute on Uranium Recovery from Seawater, where the same unclassified adsorbent was used (Ogata, 1986).

Shirai (1977) has reported that the behavior of particles in the fludized bed becomes stable when the particle size distribution is large. In the CFBA, however, the circulating fluidized region is extended when the particle size is large and its distribution is small.

Mean linear velocity of Water and Pressure Drop through the Bed

Figure 11 shows the relationship between mean linear velocity of water and pressure drop through the bed. The pressure drop between the water inlet and the water outlet was measured by a U-tube manometer. The size of the CFBA was two times larger than that shown in Figure 3, to get larger pressure drop. The contacting section height, H_c, was 300 mm, the bed width, L, was 200 mm, and bed thickness, T, was 50 mm.

The pressure drop increased sharply with the increase in the mean linear velocity to about 0.1 cm/s. In this region, I, the adsorbent was not expanded in the contacting section and the bed seemed like fixed bed. In velocity range II, from about 0.1 to 0.8 cm/s, the pressure drop was almost constant. The water–particle mixture did not ascend to the top of partition wall. Behavior of the mixture in the contacting section was similar to the fluidized bed. In velocity ranges III and IV, from 0.8 to 1.7 cm/s, the adsorbent particles began to circulate in the bed. The pressure drop decreased with increasing mean linear velocity.

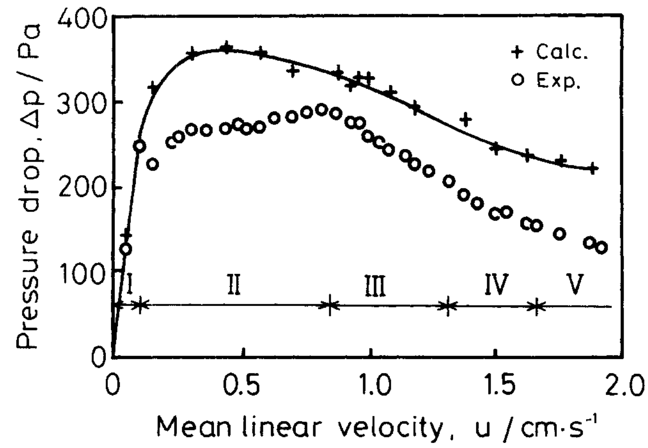

Figure 11. Relationship between mean linear velocity of water and pressure drop through bed.

CFBA used is 2X that in Figure 3 except for bed thickness; $W =$ 24%

I: Adsorbent particles are not expanded in contacting section

II: Water–particle mixture does not ascend to top of partition wall; mixture behavior is similar to fluidized bed

III: Adsorbent particles begin to circulate in bed; some amount of the adsorbent deposits in bottom of bed.

IV: Adsorbent particles circulate smoothly in bed

V: Adsorbent particles begin to carry over

The decrease of pressure drop corresponded to the amount of adsorbent suspended in the contacting section. In region III, some amount of the adsorbent deposited in the bottom of the bed. Region IV is the circulating fluidized region. At higher velocity than region IV, the adsorbent particles began to carry over.

The pressure drop in the fluidized bed is generally calculated by the following experimental expression (Shirai, 1977),

$$\Delta p = \frac{(\rho_a - \rho_f) \cdot V_p \cdot g}{A_c} \qquad (1)$$

where Δp is the pressure drop, A_c is the cross section of the contacting section, g is the gravity acceleration, V_p is the amount of suspended adsorbent, ρ_a is the wetted apparent density of an adsorbent particle, and ρ_f is the fluid density. This expression implies that the pressure drop is in proportion to the amount of adsorbent suspended in the measured section. The solid line in Figure 11 represents the pressure drop calculated by Eq. 1. V_p values were evaluated from photographs of the side view of the CFBA taken at each water velocity. The calculated values are slightly larger than the experimental data. Part of these discrepancies arise from uncertainty in the determination of the V_p values. Furthermore, Shirai has reported that Eq. 1 is not strict and the calculated values often deviate from the experimental data about 20 to 30%. We consider that Eq. 1 for the fluidized bed is also applicable to the CFBA, since the difference between calculated and experimental data in Figure 11 is within 30%.

The CFBA has no distributor such as is commonly installed in conventional fluidized beds. Thus the overall pressure drop of the CFBA including influences of the bed shape would be smaller than that of fluidized beds. Furthermore, clogging by particles in suspension in the processed water would be avoidable.

Conclusions

The CFBA, which is applicable to liquid–solid two-phase flow, has been developed in the present study. The results are summarized as follows:

1. Mean linear velocity in the CFBA is two to three times higher than that in conventional liquid-solid contacting systems.
2. The water–particle mixture is separated by collision with the surface of the packed adsorbent.
3. Both the circulating start velocity and the limit velocity are in proportion to the sinking velocity of an adsorbent particle.
4. The pressure drop in the CFBA is in proportion to the amount of adsorbent suspended in the contacting section.

It is expected that the facility area of an adsorption plant will be decreased by using this bed and the adsorption process will become economical, since the CFBA can be operated at higher velocity than in conventional liquid–solid contacting systems. We believe that the CFBA is a promising contact apparatus for recovering trace elements or removing trace contaminants from a large quantity of industrial water.

Acknowledgment

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Notation

A = total bed area = LxT, mm^2
A_c = contacting section area = $L_c xT$, mm^2
d_p = average particle size, mm
g = gravity acceleration, m/s^2
H = bed height, mm
H_c = contacting section height, mm
H_p = packed adsorbent height during operation, cm
L = bed width, mm
L_c = contacting section width, mm
L_i = water inlet width, mm
L_p = particle nozzle width, mm
Δp = pressure drop, Pa
Q = water flow rate, cm^3/s
T = bed thickness, mm
u = mean linear velocity of water = Q/A, cm/s
u_c = water velocity in contacting section = Q/A_c, cm/s
u_{max} = circulating limit velocity, cm/s
u_{min} = circulating start velocity, cm/s
u_s = sinking velocity of an adsorbent particle, cm/s
V_p = amount of suspended adsorbent, cm^3
W = packing ratio of adsorbent, %

Greek letters

α = volume fraction of particles in contacting section
ϵ_p = adsorbent porosity
ρ_a = apparent density of adsorbent particle, g/cm^3
ρ_f = fluid density, g/cm^3
ρ_t = true density of adsorbent particle, g/cm^3

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