MEASUREMENT OF JET SHAPE AND ITS DYNAMIC CHANGE IN THREE-DIMENSIONAL JETTING FLUIDIZED BEDS

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Key Words: Fluidization, Grid Zone, Cold Model, Jet, Optical Fiber, Semicylindrical Bed

Local behavior of gas and particles in a three-dimensional jetting fluidized bed grid zone was investigated. A cone-shaped distributor with a center nozzle was employed as a gas injector and the results were compared with those for a flat distributor. A semicylindrical column was used to observe the phenomena in the grid zone from the transparent flat wall by video camera. An optical fiber probe measurement was also conducted simultaneously. The signals obtained by the sensor were compared with pictures from the video recorder and correlations between the phenomena and the signals were elucidated. Periodic effusion of particles from the annulus into the jet were apparently caused by jet constriction with the same frequency. The optical fiber probe measurement method was applied to a three-dimensional cylindrical bed. The effects of gas velocity, nozzle diameter, shape of the gas distributor on jet shape, jet constriction frequency and bubble frequency were discussed. It was suggested that the momentum of gas introduced from the nozzle should be able to be used to estimate the jet diameter and the jet height. It was also found that the jet shape was drastically affected by the shape of gas distributor. The jet constriction frequency was found to increase with gas flow rate from the nozzle.

Introduction

Fluidized beds have been widely employed in gas-solid processes because of their superior properties such as high rate of heat transfer, particle mobility and capability of continuous operation. Recently, the application of fluidized beds has been extended to new processes, *e.g.*, elaboration of fine ceramics, polycrystalline silicone production and coal gasification. Because the applications of fluidized beds are expanding, various operational techniques should be established for rapid reactions, cohesive fine powder processing, and others. Several new techniques for fluidization have been developed, *e.g.*, powder-particle fluidized bed, vibrating fluidized bed, rotating fluidized bed, etc. A jetting fluidized bed is one of the techniques used to produce good circulation of particles in the grid zone between two distinct regions of the jet and the annulus with different gas compositions.

In the jetting fluidized bed, the jet height is relatively large versus the total bed height; accordingly, the contribution of the jet can be more important than that in ordinary fluidized beds. Many investigations concerned with the jet in a fluidized bed have been conducted.

Oki *et al.*⁷⁾ developed an optical-fiber array probe and investigated the behavior of the jet and particles near a distributor in a three-dimensional fluidized bed. They measured the initial bubble size, porosity profile and particle velocity with its direction. It was concluded that the orifice configuration is an important factor when studying the hydrodynamic behavior near the grid zone.

Yang and Keairns⁵⁾ studied phenomena (solids

mixing, jet constriction and slugging frequencies, slugging bed height, slug length, jet penetration height, and jet half angle) in a jetting fluidized bed. They used a 286-mm I.D. semicylindrical fluidized bed with a conical distributor and center nozzle. They concluded that solid mixing increases with an increase in jet injection velocity. They also proposed an equation for the prediction of the jet height based on the balance of inertial forces of the gas jet and the gravitational force of the bed. In another paper, they reviewed previous studies on jet height and presented their own correlation for them¹²⁾.

Tanaka *et al.*⁹⁾ measured jet height using a semicircular bed. They obtained correlations for the jet diameter and the minimum jet height. Tsukada and Horio¹⁰⁾ also measured jet height using a semicylindrical bed and presented a correlation for it. They mentioned that particle size significantly affected jet behavior. Several investigations concerning jet momentum dissipation were conducted by Behie *et al.*^{1, 2)}, Raghunathan *et al.*⁸⁾ and Wang and Han¹¹⁾. All of them used a pitot tube to measure the momentum. Behie *et al.* defined jet height as the height on the axis at which the momentum profile levels out. Raghunathan *et al.*⁸⁾ suggested the following. The jet momentum flux profile varies smoothly from jet to bubble. The jet momentum flux, which decreases with height, eventually equals that of the emulsion phase and the bed is dynamically homogeneous at this height. Frame-by-frame analysis of high-speed movies of the jet showed the height defined as above as that at which the bubbles detach from the top of the jet. Thus, it is considered that the height at which an initial bubble detaches from the jet is the most

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Fig. 1 Experimental apparatus

suitable definition of the jet height. However, in the case where a cone-shaped distributor with a center nozzle is employed as the gas injector for a fluidized bed, the jet behavior becomes more complex.

Semicylindrical beds were employed in many investigations to measure the jet diameter and the jet height as an easy and accurate method. However, the data obtained can be different from the data in a three-dimensional bed due to wall effects. Benkrid and Caram³ measured particle velocities in semicylindrical and cylindrical spouted beds. The data obtained from each bed was different. Therefore, they insisted that measurements should be conducted in real three-dimensional beds. The need for measurements in three-dimensional beds was also pointed out by Khattab and Ishida⁶.

The purpose of this study is to investigate the effects of operational conditions on jet behavior in a three-dimensional jetting fluidized bed with a conical distributor. The present results will be applied to a numerical simulation used to scale up fluidized bed reactors.

A semicylindrical fluidized bed cold model and a video tape recorder set were used to observe the motion of the jet in the grid zone from the transparent flat wall of the bed. Simultaneously, an optical fiber probe was inserted from the top of the bed and the relation between the signals of the sensor and the phenomena near the jet was elucidated.

The optical fiber technique was applied to the three-dimensional cylindrical bed and the effects of distributor design and operational conditions on the jet behavior, jet diameter, jet height and jet constriction frequency were discussed by referring to the results obtained in the semicylindrical bed experiments. From the present results, applicability of results previously reported from semicylindrical beds to three-dimensional beds will be elucidated.

1. Experimental

Figure 1 shows a schematic diagram of the experimental apparatus. A fluidized bed column of 50 mm I. D.,

Fig. 2 Gas injectors

500 mm height (Bed A), a semicircular fluidized bed of 80 mm I. D., 500 mm height (Bed B) and a circular fluidized bed of 80 mm I. D., 500 mm height (Bed C) were employed in the present study. The beds were composed of transparent acrylic resin. A circular, cone-shaped (60 deg.), multipore distributor (0.5 mm I.D., 20 orifices) with a center nozzle (6 or 3 mm I.D.) was employed as the gas injector for Bed A. A semicircular, cone-shaped (60 deg.) or a flat multipore distributor (0.5 mm I.D., 64 orifices) with a semicylindrical center nozzle (6 mm I.D.) was employed for Bed B. A circular, cone-shaped (60 deg.) or a flat, multipore distributor (0.5 mm I.D., 128 orifices) with a center nozzle (6 mm I.D.) was employed for Bed C. To distribute air homogeneously, porous material (kitchen sponge, 5 mm thick $\rho = 16.8 \text{ kg/m}^3$) was attached to the surface of the multipore plates of both gas injectors. The distributors are schematically shown in Fig. 2. When no air was introduced from the distributor, the orifices of the distributor were sealed using cellophane tape to prevent the nozzle gas from flowing into the distributor chamber. Spherical alumina particles were employed as bed material. Their average diameter and density was 0.262 mm and 1500 kg m^{-3} , respectively. The fluidized bed height was around 200 mm. Air was supplied from a compressor and it was passed through humidifiers to prevent electrostatic effects inside the bed. It was introduced independently through the nozzle and the distributor. Water kept at zero degrees centigrade was poured into the humidifiers in order to maintain a constant air humidity.

A video tape recorder (VTR) set (Victor GR-AW1 VHS-C) was used to observe the behavior of the gas and particles in the grid zone from the flat front wall of the semicylindrical Bed B. An optical sensor (Takenaka Electronic Ind. Co., Ltd., F3-RAN) with a multifiber reflection probe (Takenaka Electronic Ind. Co., Ltd., F88-022-X1) and digital oscilloscope (Yokogawa Electric Co., Ltd., DL1100) were also employed to measure jet diameter and jet height. The diameter of the probe was 1.5

Table 1. Experimental conditions

	case A (STD)	case B	case C	case D	case E	case F	case G	case H
Column diameter, mm	50	50	50	50	50	50	50	50
Column shape	C	C	C	C	C	C	C	C
Distributor shape	cone	cone	cone	cone	cone	cone	cone	cone
Nozzle diameter, mm	6	6	6	6	3	3	3	3
Gas flow rate from nozzle, u_{n0}/u_{mf}	1.5	1.0	2.0	2.5	1.0	1.5	2.0	2.5
Nozzle gas velocity [m/s]	3.5	2.3	4.6	5.8	9.2	13.8	18.4	23.0
Gas flow rate from distributor, u/u_{mf}	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

	case I	case J	case K	case L	case M	case N	case O	case P
Column diameter, mm	80	80	80	80	80	80	80	80
Column shape	S	S	S	C	C	C	C	C
Distributor shape	cone	cone	cone	cone	cone	cone	cone	flat
Nozzle diameter, mm	6	6	6	6	6	6	6	6
Gas flow rate from nozzle, u/u_{mf}	1.5	0.3	2.5	0.3	1.5	2.5	1.5	1.5
Nozzle gas velocity [m/s]	8.8	1.8	14.8	1.8	8.8	14.8	8.8	8.8
Gas flow rate from distributor, u/u_{mf}	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0

C: cylindrical, S: semicylindrical

Fig. 3 Optical fiber probe with hood

mm and it was made from a 0.05 mm 230 projector and receiver fibers bundled together. The optical fiber probe was inserted from the top of the bed. A hood was attached at the tip of the optical probe to obtain high response signals for particles moving upward, as shown in **Fig. 3**. The optical probe without the hood attached was also used for measurement of jet constriction frequency.

All experiments were conducted at ambient temperature and pressure. The experimental conditions are listed in **Table 1**.

2. Results and Discussion

2.1 Observation of gas and solid behavior in semi-cylindrical bed

In the previously described jetting fluidized bed, gas expelled from a nozzle forms a jet whose length and shape change periodically. The jet behavior is affected by the

Fig. 4 Typical jet behavior

experimental conditions.

Typical jet behavior observed by the VTR camera is illustrated in **Fig. 4**. **Figure 5** also shows the typical shape of the maximum jet during each set of conditions. When a cone-shaped distributor was used, the following behavior was observed. When the jet height was minimum (**Fig. 4 C-a**), namely during the first stage of jet expansion, a narrow jet above the nozzle was observed. As the jet grew, jet constrictions appeared twice near the bottom due to particles entering the jet (**Fig. 4 C-b,c**). The upper part of the first constriction swelled like a mushroom cap and the void between the two constrictions took the form of a mushroom stem (**Fig. 4 C-d**, **Fig. 5 (a)**). Finally the upper part of the second constriction became detached from the newly formed jet (**Fig. 4 C-e**). The “stem” was incorporated into the “cap” to form a single bubble (**Fig. 4 C-a**). When the bubble detached, the jet height was minimized again. These phenomena were observed five or six times a second. It is suggested that the jet constriction frequency is

Fig. 5 Typical pictures of maximum jet

closely related to the bubble frequency. Particles in the annulus region descended, moved along the inclined distributor wall and entered the jet with jet constriction. The observed jet diameter was relatively narrow compared with that for the flat distributor, which is possibly explained by the above phenomena. It was seen in many cases that particles also dropped into a bubble at the top of the center axis. Then, the bubble was horizontally divided into two parts and ascended near the wall.

On the other hand, when a flat distributor was employed, the minimum jet swelled at the bottom and then the constriction appeared at the bottom of the jet (Fig. 4 F-a). As the globular shaped void ascended, constrictions occurred a few times at the bottom of the jet (Fig. 5(b)). A group of two to four voids, which were separable by the constrictions, was then detached from the newly formed jet for the final time. The height at which the bubble detached was lower and the coalescent pattern of the jet constrictions was more irregular than those for the cone shaped distributor. The movement of particles descending in the annulus was not affected by the distributor wall in this case. It is also suggested that the differences in behavior of gas and solids were caused by the differences in pressure distribution and fracturation at the bottom of the bed.

In Fig. 5 (c), the observation when no air was injected from the distributor is shown. The comparison between Figs. 5 (a) and 5 (c) indicates the effect of background fluidization. Apparently, a thick and high jet was observed when the background fluidizing air was stopped. This phenomenon was explained by the observation that parti-

Fig. 6 Signal patterns obtained from optical probe with hood

cles in the annulus region did not enter the jet as much as those for the case when background fluidizing air was injected. This was because the particles in the annulus region did not become fluidized.

When the diameter of the center nozzle was reduced to 4 mm [see Fig. 5 (d)], a slightly thicker and higher jet was observed as compared with the case of Fig. 5 (a). This was due to an increase in jet gas momentum along with a decrease in nozzle diameter.

An increase in gas flow rate, u_{n0}/u_{mf} , increased the jet diameter and the jet height by a factor of up to 2.5 as shown in the Fig. 5 (e).

2.2 Measurement of jet diameter and jet height

Signal oscillation patterns obtained by the optical probe with hood were divided into seven types, as shown in Fig. 6 (No. 0: high intensity, no oscillations, No. 1: high intensity with small width oscillations, No. 2: relatively high intensity with wide width oscillations, No. 3: wide width oscillations including low intensity small oscillations, No. 4: low intensity small range oscillations with some wide width oscillations, No. 5: low intensity small range oscillations with a few wide width oscillations, No. 6: low intensity small width oscillations). The oscillation patterns were then compared with the video movie observations. The oscillation patterns of signal intensities obtained in the jet region by the optical probe were apparently different from those obtained in the annulus region. In the jet center, signal level was always high (Fig. 6, Nos. 0 and 1) because diluted particles were pneumatically transported. On the other hand, in the annulus region, signal intensity was kept low with a small amplitude (Fig. 6, No. 6). This might be caused by the fact that the descending particles hardly enter the hood. In the boundary region, some particles were moving upward while others moved downward.

Fig. 7 Typical map of signal types in bed

Fig. 8 Measurement method of jet diameter

Accordingly, the signal oscillated vigorously and the amplitude was large (Fig. 6, Nos. 2-5). The signal patterns changed from Nos. 0 to 6 in Fig. 6 as the probe was moved from the jet center to the wall. **Figure 7** shows a typical map of the signal types.

An optical fiber measurement and VTR observation were simultaneously conducted in a semicylindrical bed. The optical fiber probe was inserted from the top along the flat wall. Thus, the signal from the fiber was directly related to the visual observation. Under the conditions abbreviated as "case I" (semicylindrical bed, cone distributor, $d_n = 6$ mm, $u_{n0}/u_{mf} = 1.5$, $u_d/u_{mf} = 1.0$), the jet height observed using the VTR camera varied from 3 to 6 cm. The height from which type Nos. 1 and 0 signals were obtained from the probe corresponded to the maximum jet height of 6 cm. This was confirmed by pictures from the VTR camera showing the distance from the column center to the

Fig. 9 Effects of gas flow rate from nozzle on jet diameter

Fig. 10 Effects of gas flow rate from nozzle on jet height

boundary between signals No. 2 and 3 corresponded to the radius of the jet. From the bottom to the middle of the jet, the jet diameter gradually increased; therefore, the average jet diameter between the middle height and the top of the jet was employed as the representative jet diameter for the conditions of case I. Using this method, jet diameter and jet height were measured in the three-dimensional bed.

The jet did not necessarily stand at center axis but was found to be inclined in many cases during our study. The position of the jet center, however, hardly moved. The jet diameter at a certain height was determined by the following method, as shown in **Fig. 8**. First, the tip of the optical probe was moved horizontally and radially (line A in Fig. 8), and the center of the jet was determined from the observed signal patterns. The probe was then moved along line B perpendicular to line A.

Figures 9 and 10 show the effects of the gas flow rate from the nozzle on the jet diameter and jet height, respectively. They also show numerical predictions by Tanaka's correlations⁹⁾ for jet height (1) and for jet diameter (2),

$$h_j = 0.6 Q^{0.4} (h_j: \text{cm}, Q: \text{cm}^3/\text{s}), (u_0/u_{mf} < 7) \\ 0.31 \omega P_n [P_n / (\omega d_p)]^{1/3} (\tan \phi_r)^{2/3}, (u_0/u_{mf} > 5) \quad (1)$$

$$d_j / P_n = 0.8 (\omega d_p / P_n)^{1/3} (\tan \phi_r)^{1/3} (U_0 / U_{mf})^{3/5}, (U_0 / U_{mf} < 5) \\ 2.5 (\omega d_p / P_n)^{1/3} (\tan \phi_r)^{1/3}, (U_0 / U_{mf} < 5) \quad (2)$$

Fig. 11 Typical signals by optical probe without hood

and by Horio's⁴⁾ correlation for jet diameter(3).

$$\frac{d_j}{d_n} = 1.56 \left(\frac{f_j Fr_j}{\sqrt{k} \tan \phi} \right)^{0.3} \left(\frac{d_n}{P_n} \right)^{0.2}, f_j = 0.02$$

$$Fr_j \equiv \frac{\rho_f u_n^2}{(1 - \varepsilon_{mf}) \rho_p d_p g}, k \equiv \frac{1 - \sin \phi}{1 + \sin \phi} \quad (3)$$

An increase in the gas velocity increased both diameter and jet height. The same effects as above were also observed when the nozzle diameter was decreased, *i.e.*, the gas velocity in the nozzle was increased. These tendencies were in good agreement with numerical predictions. However, these correlations did not account for the effects of nozzle diameter. It is suggested that gas momentum introduced from the nozzle should be taken into account to explain the behavior of the gas and particles in the grid zone.

2.3 Jet constriction frequency

According to the VTR observation, particles were found to enter into the jet causing jet constrictions. Typical results of the oscillation of signal intensities obtained from the probe without the hood in the semicylindrical bed are shown in Fig. 11. The optical probe was

Fig. 12 Comparison of jet constriction frequency in semi-cylindrical bed with that in cylindrical bed ($u_n/u_{mf}=1.5$)

Fig. 13 Comparison of jet constriction frequency in semi-cylindrical bed with that in cylindrical bed ($u_n/u_{mf}=0.3$)

located at the jet/annulus boundary. The jet constriction frequency was determined by counting the number of sharp peaks on the screen of the oscilloscope. The counted frequency was compared with pictures from the video camera (VTR). It was confirmed that the jet constriction frequencies observed by the VTR corresponded to the frequencies of the sharp peaks of signal intensities of the optical probe on the screen of the oscilloscope. In order to determine the difference in this behavior between the semicylindrical and cylindrical beds, the jet constriction frequency, which gradually decreased with height and changed into the initial bubble formation frequency, was also measured in the cylindrical beds.

The results of jet constriction frequency measurements are shown in Figs. 12 and 13 and compared with those in the semicylindrical bed. The data for the cases of nozzle gas flow rates of u_n/u_{mf} 1.5 ($u_n = 8.85$ m/s) and 0.3 ($u_n = 1.76$ m/s) are shown in Figs. 12 and 13, respectively. The tendencies and absolute values of the frequencies obtained in the semicylindrical bed were the same as those in the cylindrical bed of Fig. 12. Exactly the same results were obtained in the case for a nozzle gas flow rate, u_n/u_{mf} of 2.5 ($u_n = 14.74$ m/s). It was suggested that the column shape hardly affected the jet constriction frequencies. On the other hand, when the gas flow rate from the nozzle,

Fig. 14 Effects of gas flow rate on jet constriction frequency in cylindrical bed

Fig. 15 Effects of background fluidization on jet constriction frequency in cylindrical bed ($u_{n0}/u_{mf} = 1.5$)

u_{n0}/u_{mf} was 0.3, slightly smaller values for the jet constriction frequency were obtained in the semicylindrical bed as compared to those in the cylindrical bed of Fig. 13. This difference is explained by the fact that the gas flow rate introduced from the nozzle was too small to form a jet at the nozzle exit, thus the injected air formed small bubbles at the bottom of the bed. Passage of the bubbles thus formed was therefore easily affected by the existence of the vertical flat wall of the semicylindrical bed.

Under all conditions, the constriction frequency of the jet was high at the bottom of the jet where constriction was initiated. Typical results concerning the change in frequency with height are shown in Fig. 14 for the three-dimensional bed. The constriction frequency decreased remarkably with height in the lower part of the jet and then gradually decreased to a plateau at around 5 to 10 cm. The frequency began to decrease at above 10 cm where bubbles were formed at the top of the jet.

These phenomena are explained as follows. At the bottom of the jet (below 10 mm), scattered particles enter into the jet and the particle entering frequency is high. The middle part of the jet corresponds to the jet stem region where a permanent jet exists and constrictions ascend. In the upper part of the jet where initial bubbles form, some of the constrictions are incorporated into one bubble and

Fig. 16 Effects of distributor shape on jet constriction frequency in cylindrical bed

the constriction frequency decreases.

It is suggested that particles mainly enter into the lower part of the jet based on the observation that the jet constriction frequency was higher in the lower part of the jet than that in the higher part of the jet. Figure 14 also shows the effects of gas flow rate from the nozzle on the jet constriction frequency. An increase in the gas flow rate increased the jet constriction frequency. This result indicates that the increase in gas flow rate increases the flux of particles into the jet.

Figure 15 shows the effect of the presence of annulus gas flow from the distributor on the jet constriction frequency in the case where the gas flow rate, u_{n0}/u_{mf} , introduced from the nozzle was 1.5 ($u_n = 8.85$ m/s). When no air was introduced from the distributor, the measurements were conducted under two conditions. One was the case where the holes of the distributor were sealed by cellophane tape to prevent the nozzle air from entering into the distributor chamber, while the other case was when the holes were open. From a comparison of the results of jet constriction frequency with and without background fluidization, it was found that the observed jet constriction frequencies were almost the same. In the case where the distributor gas was stopped and the holes in the distributor were open, the observed constriction frequencies above 5 cm were lower than that for the sealed gas distributor. It is suggested that the nozzle air escaped into the distributor chamber when the holes of the distributor were not sealed.

Figure 16 shows the effects of distributor shape on jet constriction frequency. When a cone shaped distributor was employed, the constriction frequency was slightly higher than that for a flat distributor. It is proposed that when a cone-shaped distributor was employed, many more particles were introduced into the jet at the bottom of the bed as compared to using a flat distributor. This might be caused by differences in the effect of the inclined wall and in the pressure distribution profile in the bed. When a flat distributor was used, the jet was thick and the initial bubble formed at a lower point than that for a cone distributor. Many more constrictions were then incorporated into the

initial bubbles; therefore, the observed jet constriction frequency was lower than that for a cone-shaped distributor. From this figure, we can also see that the jet height at which the frequency decreased was higher in the case of a cone shaped distributor compared to that of a flat distributor. These phenomena observed using the optical fiber probe in the three-dimensional bed are in good agreement with the VTR observation in the semicylindrical bed, as already mentioned in chapter 2.1.

Conclusions

The measurement methods of jet diameter, jet height and jet constriction frequency were established by comparison of optical fiber signals with phenomena observed by a VTR system. Periodic effusion of particles from the annulus into the jet was apparently caused by jet constriction with the same frequency. It was indicated that a bubble was formed from two or more successive jet constrictions. These phenomena were confirmed by VTR observation in the semicylindrical bed.

Signal peak frequency from the optical fiber probe corresponded to the jet constriction frequency observed in the semicylindrical bed. The same signal in the jet was observed in the three-dimensional bed, which, from a comparison of the signals from the two beds, suggests the same phenomena as in the semicylindrical bed.

Optical fiber signals corresponding to the top of the jet and the jet/annulus boundary were determined in the semicylindrical bed by a comparison of the signals with VTR observations. Jet height and jet diameter in the three-dimensional bed were determined from their corresponding signals. An increase in the gas flow rate increased both diameter and height of the jet. Also, the same effects as above were observed when the nozzle diameter was decreased, *i.e.*, the gas velocity in the nozzle was increased. The presence of a conical wall affected particle movement, making the jet narrow and high when a cone-shaped distrib-

utor was employed.

Nomenclature

d_j	= jet diameter	[m]
d_n	= nozzle diameter	[m]
d_p	= particle diameter	[m]
Fr	= Froude number	[-]
g	= gravitational acceleration	[m/s ²]
h_j	= jet height	[m]
P_n	= nozzle pitch	[m]
Q	= gas flow rate	[cm ³ /s]
u_0	= superficial gas velocity	[m/s]
u_{mf}	= minimum fluidization velocity	[m/s]
u_n	= gas velocity at nozzle exit	[m/s]
u_{n0}	= superficial gas velocity at the column introduced from the nozzle	[m/s]
ϵ_{mf}	= void fraction at minimum fluidization	[-]
ρ_f	= fluid density	[kg/m ³]
ρ_p	= particle density	[kg/m ³]
ϕ_r	= angle of repose	[rad]
ω	= nozzle orientation factor, 1 for square pitch and $\sqrt{3}/2$ for triangular pitch	[-]

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