Fluidic Conveying of Chips Through a Horizontal Pipe

By Nobuhiko NISHIWAKI ** and Sankei HORI ***

In order to accomplish the automation of machining process completely, chips must be continuously conveyed from machine tools to the disposal system by mechanical and fluidic methods. The latter method is more suitable for conveying chips produced under wet condition than with the former, but the mechanism of conveying chips through a horizontal pipe has not yet been clarified.

Therefore, in this study the mechanism of hydraulic conveying of chips has been experimentally analyzed. From the results, it was found that the drag coefficient of conveying chips estimated with the representative area, obtained from the number of chips per unit volume, and maximum relative velocity is nearly constant within a range of Reynolds numbers from 20 to 10000. In addition, it was revealed that the maximum velocity for conveying chips through the pipe can be approximately estimated by using the void ratio and the number of chips per unit volume.

Key Words : Chips, Fluidic Conveyor, Drag Coefficient, Settling Velocity, Conveying Condition, Manufacturing Technology, Machine Tool

1. Introduction

Chips are produced continuously whenever a machining operation is in progress and they must be collected as close to the cutting zone as possible and speedily taken away to enhance the productivity. At present, the removal of chips is one of the important problems to be considered in order to accomplish an unmanned machining system completely. For this reason, mechanical, pneumatic, and hydraulic methods are proposed for conveying chips and some of them are in practical use⁽¹⁾.

The mechanical methods are often used in machine shops and there are many different types of mechanical conveyors. The pneumatic method is suitable to the collection of swarf chips and dust at the point of creation. Generally, chip and dust extraction is effected by locating a zone of air entrainment as close as possible to the zone of swarf production. In the hydraulic method, a continuous stream of cutting fluid is used to convey the chips to a disposal point through a channel or a circular pipe, after the chips are washed away from the cutting zone into a trench. In addition, by using a hydraulic system, it is possible to convey almost all types of swarf.

Of these three methods for conveying chips, the mechanical method is most wide-

ly used at present. However, the chip remaining on flat machine tool surfaces can not be removed without assistance of workers or cutting fluid.

Thus, it may be said that the mechanical method is a semi-automatic system. Adopting the hydraulic method, it will be possible to save the labour to remove the chips from the machine tool surfaces. However, the necessary flow rate and velocity of the conveying fluid in designing and controlling the hydraulic conveying system have not been fully clarified in the former works⁽²⁻⁴⁾, and the fluidic conveying devices must be adjusted in accordance with each machine and type of chips.

In this paper, the flow velocity of the conveying fluid and the conveying speed of chips in a circular pipe placed horizontally are experimentally evaluated, changing the shape of chips. In addition, the settling speed, which is an important factor to separate the chips from the cutting fluid, was investigated.

2. Experiments

Fig.1 shows an outline of the experimental apparatus used in the experiments. In the figure, the conveying fluid is constantly supplied by a pump (9) from a tank (10) to the pipe (1) placed horizontally, and returned to the tank (10) through another pipe. The circular pipe is made of acrylic resin. The flow rate can be adjusted using two valves (8). The chips produced in metal cutting are fed into the horizontal pipe (1) through the vertical pipe (2), and then the pumped fluid conveys the chips into the horizontal pipe. Finally, the chips are collected on a wire net (3).

In the experiments, two different diameters of the horizontal pipe (1) are

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** Associate Professor,
Tokyo University of Agriculture
and Technology,
2-24-16 Nakamachi, Koganei, Tokyo.

*** Research Assistant,
Tokyo University of Agriculture
and Technology,
2-24-16 Nakamachi, Koganei, Tokyo.

used. The diameter and length are shown in Fig.1. When chips are conveyed, the conveying speed and the shapes of the chips in the pipe are recorded by means of a camera ⑥ and a stroboscope ⑦ as shown in Fig.1. For easy observation of chips being conveyed, a rectangular tank 5 filled with the same fluid as the conveying fluid was attached outside the pipe.

The flow velocity and its distribution in the pipe were detected by a Pitot tube ④ of which outer diameter is 2.0 mm as shown in Fig.1. As the conveying fluid, water and oil were mainly used. Their kinetic viscosity and specific weight are shown in Table 1.

In the experiments, the conveying fluid is constantly supplied to the horizontal pipe ①, and then chips are put into the pipe through the vertical pipe ②, after being washed with trichlorethylene. The conveying speed and shape of chips are measured by means of a camera and a stroboscope. About 200 measurements were carried out using the same kind of chips. The relationship between the shape and the conveying speed of chips was investigated. In addition, the characteristic shape and the average conveying speed were evaluated.

The flow velocity of the fluid which

is needed to move chips at rest on the inner wall of the pipe was measured. In the experiments, chips were transported one by one to the point at a distance L_2 from the tank. After that, when flow rate is gradually increased, the chips start to move at a certain flow velocity. This starting velocity was measured by a Pitot tube, changing the conveying medium. Air was used as the conveying medium only in this measurement to compare with water and oil, and a turboblower was used to supply the air instead of the pump 10. In this case, chips are transported to the point at a distance 3800 mm from the inlet (5K6) of the horizontal pipe of which diameter and length are 40 mm and 4000 mm respectively.

The drag coefficient of chips in static fluid was investigated, using another tank made of acrylic resin. The tank is 700 mm high, 80 mm wide and 100 mm deep. After removing bubbles from the chips, they were put into the tank. The mean settling speed was measured for about 100 pieces of the same kind of chips using a camera and a stroboscope.

The coefficient of static friction between the wall of the pipe and the chips was estimated from the inclination angle of the pipe. The measurements were carried out under the following two conditions: the pipe in dry condition and the pipe filled with either water or oil.

3. Chips Used in the Experiments

In order to investigate the influ-

Table 1 Kinetic viscosity and specific weight of conveying fluid

	Water	Oil
Kinetic viscosity, ν (m ² /s)	1.00×10^{-6} (293K) 0.74×10^{-6} (308K)	0.88×10^{-4} (293K) 0.36×10^{-4} (308K)
Specific weight, γ_f (N/m ³)	9.8×10^3 (293K, 308K)	8.4×10^3 (293K, 308K)

Fig. 1 Outline of experimental apparatus

Fig. 2 Kinds of chips used in the experiments

ence of the raw material of chips on the conveying mechanism, the following three kinds of materials were used; semi-hard steel, brass and aluminum alloy. Their specific weights are shown in Table 2. In addition, various shapes of chips shown in Fig.2 were prepared. These chips were produced by turning, milling, shaping and drilling under different cutting conditions. The dimensions of chips were measured for about 200 pieces of the same kind of chips as shown in Fig.3. The mean diameter d_m , length l_m , weight W_m and their standard deviations σ are shown in Table 3. In the table, N is the number of chips per unit volume and ε is the void ratio of chips. The void ratio ε is

$$\varepsilon = (V - (W_s/\gamma_s))/V \quad (1)$$

where W_s is the total weight of chips in the volume V , and γ_s is the specific weight of raw material of chips. The total weight of chips is given by

$$W_s = W_m N V \quad (2)$$

where W_m is the mean weight of the same kind of chips. Combining Eqs.(1) and (2), and rearranging gives

$$N = (1 - \varepsilon) \gamma_s / W_m \quad (3)$$

As shown in Fig.2 and Table 2, small size chips are used in the experiments. Probably, the diameter of the pipe may be small compared with the pipe in practical use. In addition, long chips are not adopted, because the handling of such long chips is considerably difficult, and the fluidic conveying is not suitable to the transportation of long chips. In future, such long chips will not be produced in metal cutting process with the advance in the technology of chip breaking.

Table 2 Average values of dimensions, weight, and their standard deviation of same kinds of chips

No.	γ_s (N/m ³)	l_m (σ) (mm)	d_m (σ) (mm)	W_m (σ) (10 ⁻³ N)	N (10 ³ No./m ³)	ε (%)
1	7.67	21.3 (4.32)	5.65 (0.72)	3.67 (0.98)	0.14	93.2
2	$\times 10^4$	28.7 (3.67)	3.35 (0.18)	2.23 (0.31)	0.131	96.2
3		9.55 (2.93)	5.75 (0.48)	1.21 (0.42)	0.558	91.2
4		4.61 (0.59)	3.76 (0.20)	0.461 (0.017)	1.90	87.8
5		8.10 (1.17)	7.40 (0.58)	0.405 (0.016)	0.909	95.2
6		16.4 (2.04)	8.60 (0.77)	0.673 (0.024)	0.399	96.5
7		28.8 (4.49)	5.55 (0.31)	1.59 (0.26)	0.304	93.7
8		2.55 (0.15)	3.00 (0.03)	0.216 (0.037)	8.38	76.4
9		1.50 (0.06)	1.50 (0.20)	0.108 (0.011)	20.5	71.1
10		1.60 (0.42)	4.35 (0.80)	0.284 (0.071)	2.11	92.2
11		31.1 (4.15)	7.70 (0.34)	6.52 (0.56)	0.0835	92.9
12		76.6 (18.3)	9.65 (0.61)	18.4 (2.88)	0.00834	98.0
13	8.24	7.00 (0.39)	3.25 (0.65)	0.627 (0.030)	2.18	83.4
14	$\times 10^4$	3.15 (0.09)	2.50 (0.19)	0.216 (0.006)	6.07	84.1
15	Brass	19.2 (0.004)	1.07 (0.06)	0.356 (0.003)	1.60	93.1
16	2.73	17.5 (3.60)	6.80 (1.23)	1.65 (0.49)	0.0794	95.2
17	$\times 10^4$	15.0 (3.07)	5.45 (0.99)	0.745 (0.019)	0.161	95.6
18		17.2 (4.77)	4.05 (0.80)	0.461 (0.013)	0.255	95.7
19	Al-alloy	3.80 (0.66)	4.25 (0.05)	0.0980 (0.002)	1.87	93.3
20		4.20 (1.40)	3.50 (0.90)	0.147 (0.008)	5.20	72.0
21		2.60 (0.99)	2.95 (0.67)	0.0490 (0.001)	5.79	89.6
22		40.8 (2.62)	7.49 (0.39)	2.31 (0.18)	0.0331	97.2
23		48.9 (4.04)	10.3 (0.59)	4.73 (0.42)	0.0139	97.6

Fig. 3 Definition of representative length and diameter

4. Experimental Results and Discussions

4.1 Settling behaviour and drag coefficient of chips.

When a chip is conveyed to a certain point of the horizontal pipe, the chip slides on the inner wall of pipe and is subjected to the friction force. This friction force balances with the drag which the chip receives from the conveying fluid at constant flow velocity. It is, however, difficult to evaluate the drag coefficient C_d , the representative area A of chips, and the representative relative velocity between the fluid and the chip, due to the complicated shape of chips and nonuniform velocity distribution in the radial direction of the pipe.

Thus, in this paper, for evaluating the drag coefficient C_d and the representative area A of chips, the steady settling speed of chips was measured in a static fluid. In this experiment, a rectangular tank made of acrylic resin was used. When the settling speed of chips has become constant, the difference in the weight of one chip W and the buoyancy balances with the drag. Their relation is

$$W(\gamma_s - \gamma_f)/\gamma_s = C_d A \gamma_f U^2 / 2g \quad (4)$$

where γ_f is the specific weight of fluid, U is the steady settling speed of a chip and g is the gravity acceleration. Rearranging Eq.(4) gives the following equation.

$$C_d = (W(\gamma_s - \gamma_f)/\gamma_s) / (A \gamma_f U^2 / 2g) \quad (4')$$

Usually, the drag coefficient is a function of Reynolds number and the projected area of a chip on an orthogonal plane to the stream line is employed as the representative area A .

The settling behaviour was obtained using chips shown in Table 3. Their typical shapes are shown in Fig.3. From the observation, it was found that in oil only the 19th chip settles keeping its axis vertical, and the other chips settle keeping their axes horizontal. In water, all kinds of chips settle swaying a little and their settling pattern is similar to that in oil. The diameter d and length l of the chips were measured as shown in Fig.3, and the drag coefficient C_d was obtained from Eq.(4). In this case, $\pi d^2/4$ and dl are adopted as the representative area of the 19th chip and that of the others respectively. Also, Reynolds number Re of a settling chip was calculated using the diameter d as the representative length, and the relationship between C_d and $Re (= U_s d / \nu)$ was investigated.

From the results shown in Fig.4(a),

Table 3 Kinds of chips adopted for observation of settling behaviour and conveying behaviour

	Kinds of chips
For settling experiments of a chip.	1,2,4,7,13,14,16,17,19,22,23,
For conveying experiments of a chip.	2,7,8,10,11,12,13,16,18,22,23,

it is found that the drag coefficient C_d is affected by Reynolds number and the shape of chips. This relation can not be applied to the practical use if the settling pattern of chips is not defined. It is more useful to evaluate the drag coefficient C_d only from Reynolds number, for the separation of chips from the conveying fluid.

In order to eliminate the effect of the settling pattern of chips, another representative area and length were defined as $(\pi d^2/4)^{2/3}$ and $(\pi d^2/4)^{1/3}$ respectively. The results of re-calculating using these alternative values are shown in Fig.4(b). As shown in the figure, the scatter of data is considerably small as compared with the data shown in Fig.4(a). Thus, it may be concluded that the settling speed of a chip can be estimated from Fig.4(b) and the dimensions and weight of the chip approximately.

In the case of large quantities of chips being separated from the conveying fluid, the mean settling speed of many chips produced under the same cutting conditions is more useful than the settling speed of each chip. In such case, it is more practical to evaluate the representative area from the number of chips per

(a) Utilization of the representative area evaluated from the projected area of chips on an orthogonal plane to the settling direction

(b) Utilization of the representative area evaluated from the apparent area of chips

Fig. 4 Relationship between the drag coefficient and Reynolds number

unit volume than from the mean values of the dimensions of each chip. Hence, the relationship between the mean volume $\pi d_m^2 l_m / 4$ of chips and the reciprocal of the number of chips per unit volume N was investigated, where, the subscript m indicates the mean value. As shown in Fig.5, N is in inverse proportion to $\pi d_m^2 l_m / 4$. Therefore, $N^{-1/3}$ and $N^{-1/3}$ can be employed as the representative area and length respectively.

In the experiments, the mean settling speed U_{sm} was evaluated for about 100 pieces of the same kind of chips in the same manner as in the measurement aforementioned, and the relationship between C_{dm} and R_{sm} was investigated. The results are shown in Fig.6. The mean settling speed can be estimated from the figure if the number of chips per unit volume N and the mean weight of chips W_m are known.

From the above results, it can be concluded that the mean drag coefficient can be calculated using the representative area obtained from the number of chips per unit volume. Moreover, the drag coefficient C_d is nearly equal to 1.0 within the range of Reynolds numbers from 10^2 to 10^4 .

Fig. 5 Relationship between the apparent mean volume and the number of chips per unit volume

Fig. 6 Relationship between the mean drag coefficient and Reynolds number

4.2 Coefficient of friction. As mentioned above, a chip being conveyed receives not only the drag but also the frictional force from the wall of the pipe placed horizontally. Thus, it is very important to evaluate the coefficient of kinetic friction μ . However, in this section, only the coefficient of static friction μ_s was investigated, since the measurement of the kinetic friction force is considerably difficult. The results are shown in Table 4. The coefficient of static friction μ_s varies from 0.5 to 0.7 and is not affected by the raw material of chips and the conveying fluid. Therefore, it may be supposed that the coefficient of kinetic friction μ is not affected by the raw material of chips and the conveying fluid as well as μ_s .

4.3 Behaviour of a chip being conveyed. The chips being conveyed receive both the drag from the conveying fluid and the frictional force from the wall of the pipe, and these two forces are in equilibrium. Thus, their relation is given by the following equation,

$$\mu W(r_s - r_f)/r_s = C_d A r_f (U_f - U_s)^2 / 2g \quad (5)$$

where U_f is the representative velocity of the conveying fluid corresponding to the chip, and U_s is the conveying speed of chip.

For evaluation of the representative velocity U_f of the conveying fluid, it is necessary to grasp the flow velocity distribution of fluid and the shape of chips being conveyed in the pipe placed horizontally. From the measured flow velocity distribution, the following relations were obtained; (1) the flow in pipe is turbulent when using water and air as the conveying medium, and the range of Reynolds numbers obtained from the mean flow velocity in the pipe is from 1×10^4 to 7×10^4 , and (2) in usage of oil, the flow is laminar and Reynolds number varies from 450 to 1200. From the above facts, the velocity distributions in steady flow are given by

$$U_f = U_m(y/R)^{1/7} \quad (6)$$

and

$$U_f = U_m(2(y/R) - (y/R)^2) \quad (7)$$

where y is the distance from the inner wall of the pipe, U_m is the maximum flow velocity, and R is the radius of the pipe.

It is important to observe the conveying shape of various chips in the pipe as well as the settling pattern. From the observation, it is found that when the length l is greater than the diameter d of the chip, its axis is parallel to the stream line and when l is smaller than d , the axis is perpendicular to the stream line. Moreover, the chip is con-

veyed sliding on the wall of the pipe. Therefore, the representative flow velocity U_f can be obtained by substituting $y=d/2$ or $y=l/2$ into Eqs.(6) and (7) usually. However, the representative relative flow velocity $U_f - U_s$ becomes negative in some cases. For this reason, the representative flow velocity U_f was calculated by substituting $y=d$ or $y=l$ into Eqs.(6) and (7).

As the representative area of a chip A , the projected area on an orthogonal plane to the stream line was used considering the conveying shape of chip.

Consequently, $A = \pi d^2/4$ ($l < d$) and $A = dl$ ($l > d$) were adopted.

Generally, it is not easy to measure the coefficient of kinetic friction μ and the drag coefficient C_d of conveyed chips in the pipe placed horizontally. In this

(a) Utilization of the representative area evaluates from a projected area to an orthogonal plane to the stream line

(b) Utilization of the representative area evaluated from the apparent volume of chips

Table 4 Coefficients of static friction

	Air	Water	Oil
Semi-hard steel	0.51	0.49	0.55
Brass	0.58	0.53	0.59
Aluminum alloy	0.59	0.58	0.67

Fig. 7 Relationship between the apparent weight and the apparent drag

study, it was assumed from the results of the above section that the coefficient of kinetic friction has a constant value, and is not affected by the raw material of chips and the conveying medium. In addition, the drag coefficient C_d was kept constant referring to the results of the settling experiments, since Reynolds number $Re (=h(U_f - U_s)/\nu)$ in water and oil varied from 200 to 5000 and from 10 to 100 respectively.

Thus, from the above considerations, the apparent weight considering the buoyancy is proportional to the apparent drag of the conveying fluid acting on the chip.

To verify the relation mentioned above, the various kinds of chips shown in Table 3 were conveyed. The relationship between the apparent weight and the apparent drag is shown in Fig.7(a). It can be seen from the figure that the data are scattered although the mutual relation considerably well holds. Hence, the data were rearranged as shown in Fig.7(b), using the representative area defined as $(\pi d^2 l / 4)^{2/3}$. It can be seen from the figure that the scatter of these data is less than that of the data shown in Fig.7(a) and the apparent weight is in proportion to the apparent drag. Therefore, the relation is given by

$$W(\gamma_s - \gamma_f) / \gamma_s = A \gamma_f (U_f - U_s)^2 / 2g \quad (8)$$

$$\text{where, } A = (\pi d^2 l / 4)^{2/3} \quad (9)$$

Thus, it can be concluded that Eq.(9) is suitable to the expression of the representative area.

4.4 General behaviour of the chips being conveyed. As mentioned above, it is necessary to transport large quantities of chips produced under the same cutting conditions. Then, it is important to grasp the general behaviour of the chips in the conveying fluid.

In the experiments, about 200 pieces of chips produced under the same cutting conditions were prepared for each kind. The chips were conveyed one by one at a constant flow rate, and then the mean

Fig. 8 Relationship between the apparent mean weight and the apparent mean drag of same kinds of chips

conveying speed of the chips was measured. In this case, $N^{-2/3}$ is adopted as the mean representative area considering the results about settling of chips, and the flow velocity at the distance from the wall, which is equal to the mean diameter or length of chips, was adopted as the mean representative velocity U_{fm} . Also, the mean weight W_m was used as the weight of the chips.

Fig.8 shows the relationship between the mean apparent drag acting on the chip ($N^{-2/3} \gamma_f (U_{fm} - U_{sm})^2 / 2g$) and the mean apparent weight of the chips considering the buoyancy ($W_m (\gamma_s - \gamma_f) / \gamma_s$). As shown in the figure, the mean apparent drag is in proportion to the mean apparent weight. Therefore, the mean drag coefficient C_{dm} acting on the same kind of chips is given by the following equation,

$$\frac{C_{dm}}{\mu} = \frac{2g W_m (\gamma_s - \gamma_f) N^{2/3}}{\gamma_s \gamma_f (U_{fm} - U_{sm})^2} \quad (10)$$

In this case, it is assumed that the Reynolds number is equal to $N^{-1/3} (U_{fm} - U_{sm}) / \nu$. Therefore, as shown in Fig.9, the relationship between C_{dm} / μ and Re_m can be obtained from the results shown in Fig.8. From Fig.9, it can be seen that C_{dm} / μ is given by

$$0.5 < C_{dm} / \mu < 1.5 \quad (20 < Re_m < 10^4) \quad (11)$$

and is independent of Reynolds number within the range from 20 to 10,000. In addition, it may be considered that the mean drag coefficient C_{dm} has a constant value since the coefficient of kinetic friction μ is independent of Reynolds number.

The flow velocity to move a chip at rest was measured. In this experiment, about 100 pieces of the same kind of chips were used, and the mean value U_{fm} of the representative relative velocity was evaluated. In this case, the following equation can be obtained from the balance of both forces.

$$\mu W_m (\gamma_s - \gamma_f) / \gamma_s = C_{dm} N^{-2/3} \gamma_f U_{fm}^2 / 2g \quad (12)$$

Fig.10 shows the relationship between the mean apparent drag and the mean apparent weight. It can be seen from the figure that the mean apparent drag is 1.5 times larger for the same value of the mean apparent weight than the results shown in Fig.8. It may be considered

Fig. 9 Relationship between the drag coefficient and Reynolds number of same kinds of chips conveyed

that the difference between the two results mentioned above is due to the difference in the coefficient of friction, that is, the difference between the static and the kinetic frictions. The reason is as follows: the 2nd root of the product of $(2g/v^2\gamma_f)$ and each mean apparent drag shown in Figs.8 and 10 is equal to the Reynolds number R_e for the chip, and the range of R_e is nearly equal in both results. Therefore, there is little difference between both drag coefficients.

From the above consideration, the relationship between the coefficients of static and dynamic frictions is given by the following equation approximately,

$$\mu_{st} \approx 1.5\mu \quad (13)$$

When the mean value of the coefficient of static friction ($\mu_{st} \approx 0.57$) shown in Table 4 is adopted, the coefficient of kinetic friction μ is 0.37 approximately.

Thus, the range of the drag coefficients can be obtained from Eq.(11) as follows,

$$0.19 < C_{dm} < 0.57 \quad (20 < R_e < 10^4) \quad (14)$$

Hence, if μ and μ_{st} can be estimated by some methods, the mean value of the representative velocity U_{Fm} may be evaluated by substituting Eq.(12) into Eqs.(7) or (9). Combining Eqs.(3) and (9), and rearranging gives

$$U_{Fm} = \sqrt{\frac{\mu_{st}}{C_{dm}}} \sqrt{\frac{2g(1-\epsilon)(\gamma_s - \gamma_f)}{\gamma_f N^{1/3}}} \quad (15)$$

In this study, from Eqs.(8) and (10), the following equation is obtained.

$$U_{Fm} = (1.0 \sim 1.7) \sqrt{2g(1-\epsilon)(\gamma_s - \gamma_f)/\gamma_f N^{1/3}} \quad (20 < R_{em} < 10^4) \quad (15')$$

U_{Fm} in Eq.(15) indicates the flow velocity for the average height of chips (d_m or l_m).

For practical use, it is important to evaluate the approximate value of the maximum flow velocity rather than the representative relative velocity. In other words, using $N^{-1/3}$ which is the representative length for the same kind of chips, the mean value of the maximum flow velocity U_v is suitable to the prac-

Fig. 10 Relationship between the apparent weight and the apparent drag when chips start to move

tical use. If U_v obtained by substituting $y = N^{-1/3}$ into Eqs.(6) or (7) is equal to U_{Fm} given by Eq.(15), U_{Mm} is

$$U_{Mm} \approx \sqrt{\frac{\mu_{st}}{C_{dm}}} \sqrt{\frac{2g(1-\epsilon)(\gamma_s - \gamma_f)}{\gamma_f}} R^{1/7} N^{-5/42} \quad (16)$$

(for turbulent flow; air and water)

$$U_{Mm} \approx \sqrt{\frac{\mu_{st}}{C_{dm}}} \sqrt{\frac{2g(1-\epsilon)(\gamma_s - \gamma_f)}{\gamma_f}} \times \frac{RN^{1/6}}{(2 - (N^{-1/3}/R))} \quad (17)$$

(for laminar flow; oil)

The relationship between both sides of Eqs.(16) and (17) when $\sqrt{\mu_{st}/C_{dm}}$ is equal to 1.0 was calculated, corresponding to the data shown in Fig.10. The results are shown in Fig.11. In the figure, two full lines show the theoretical results for $\sqrt{\mu_{st}/C_{dm}} = 1.0$ and 1.7. It can be seen that the experimental values come between both lines.

Consequently, if the void ratio ϵ , the coefficient of friction μ_{st} , the number of chips per unit volume N , and the specific weight of chips γ_s and fluid γ_f are known, an approximate value of the flow velocity to convey the chips can be obtained from Eqs.(14) and (16).

Finally, it is important to investigate the suitable shape, size and raw material of chips to the fluidic conveying. As shown in Fig.5, the relation between the number of chips per unit volume and the dimensions of the chips is given by

$$N^{-1} \approx \pi d_m^2 l_m / 4 \quad (18)$$

Combining Eqs.(3) and (18), and rearranging Eq.(16) for the turbulent flow gives U_{Mm} , that is,

$$U_{Mm} \approx \sqrt{\frac{\mu_{st}}{C_{dm}}} \sqrt{\frac{2g(\gamma_s - \gamma_f)}{\gamma_s \gamma_f}} \times R^{1/7} \left(\frac{\pi}{4}\right)^{-5/21} W_m^{1/2} l_m^{-5/21} d_m^{-16/21} \quad (19)$$

Thus, it is found from Eq.(19) that the mean value of the maximum flow velocity U_{Mm} in a pipe placed horizontally in order to convey the chips at rest is in proportion to the values of $W_m^{1/2}$, $l_m^{-5/21}$ and $d_m^{-16/21}$. In other words, the light and long helical chips with large diameter can be conveyed by the fluid easily.

Fig. 11 Necessary mean value of maximum flow velocity for conveying chips at rest

5. Conclusions

In this paper, the conveying mechanism of the chips by means of the fluid has been investigated experimentally. Also, some theoretical considerations have been done. From this investigations, the following conclusions can be drawn.

(1) It is necessary to evaluate the drag coefficient of the chip in uniform flow, using the representative area defined by either the number of chips per unit volume or the volume of a chip. The mean drag coefficient of chips in the conveying fluid has a constant value.

(2) The coefficient of friction between a chip and the wall of the pipe is independent of the raw material of chips and the kind of conveying fluid, and the static friction force is approximately 1.5 times the kinetic friction force.

(3) The approximate value of the necessary flow velocity to convey the chips can be calculated using the proposed equations, if the void ratio, the coefficient of friction and either the number of chips per unit volume or the volume of a chip are known.

In addition, it was found that the light and long helical chips with large diameter can be conveyed by means of the fluidic conveying system easily.

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References

- (1) Gough, P.J.C, Swarf and Machine Tools, (1970), 1, Hutchinson.
- (2) Minato, K., et al., J. of JSPE, (in Japanese), 39-6, (1973), p596.
- (3) Minato, K. and Toyoshima, T., J. of JSPE, (in Japanese), 436, (1977), p708
- (4) Minato, K. and Toyoshima, T., J. of JSPE, (in Japanese) 43-7, (1977), p849.
- (5) Bowles, D.J. and Brighton, J.A., Trans. of ASME, Ser. J, 90-3, (1968), p431.
- (6) McComas, S.T., Trans. of ASME Ser. J, 89-4, (1967), p847.
- (7) Ikemori, K., Science of Machine, (in Japanese), 23-1, (1971), p275.