(H_2O) = volume concentration of water vapor in the air
 $[\text{H}_2\text{O}]$ = surface concentration (coverage) of adsorbed water
 k = rate constant
 K = equilibrium constant
 L = length of the tube
 n = number of successive runs of the entire lot of beads
 N_+ = number of positive beads
 N_- = number of negative beads
 N_0 = number of neutral beads
 $[\text{OH}]$ = surface concentration (coverage) of adsorbed OH
 T = accumulated total time spent by each bead in the tube in n runs
 T = subscript for tube
 q = average absolute charge in arbitrary units
 q_+ = average positive charge in arbitrary units
 q_- = average negative charge in arbitrary units
 α = inclination of the tube to the horizontal
 ϑ = time interval between beads, $\vartheta = 1/f$
 θ = coverage of the surface
 τ = time spent by a bead in the tube in one passage, $\tau = \sqrt{\frac{2L}{g}} \operatorname{cosec} \alpha$

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MONTE CARLO SIMULATION OF HORIZONTAL PNEUMATIC CONVEYING BASED ON THE ROUGH WALL MODEL*

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On the basis of wall roughness, a simple model is presented to explain the irregular bouncing phenomena of particles in pneumatic conveying. By introducing a random factor to the model, a pneumatic transport process was simulated by Monte Carlo method.

The model could fairly well account for the concentration and velocity distribution and the rate of revolution of particles. Even very small degree of roughness was found to have a great influence upon the behaviour of particles.

In pneumatic conveying, irregular bounce due to the irregularities of particle shapes and/or the roughness

of wall surface may be considered to be the major mechanism for the suspension of particles in horizontal pneumatic transport.

In a previous paper³⁾, the irregular bouncing model based on an ellipsoid approximation of particle shape was

* Received on January 31, 1970

Presented at the 2nd Autumn Meeting (at Nagoya, Oct. 1968) of the Society of Chemical Engineers, Japan.

Fig. 1 Schematic representation of rough wall model

proposed to account for particle suspension, and a pneumatic transport process was simulated by Monte Carlo method on a high-speed computer.

In this paper, a two-dimensional irregular bouncing model based on the roughness of wall surface is presented and applied to the simulation of an actual pneumatic transport process. The results are compared with experiments in terms of concentration distributions, velocity profiles and rotational speeds of particles measured by the photographic technique.

1. Experiment

The transport line and the particles used in the present work were described in detail in a previous paper³⁾. In brief, the apparatus is made of a glass rectangular duct

* The coordinates (x' , y') are given at each time when a particle approaches to the distance of A_r from the wall surface.

** If the particle contacts with the wall at $x' = x_c'$, the velocity components of the particle in the tangential coordinates are expressed as

$$\begin{aligned} U_p &= u_p \cos \beta + v_p \sin \beta \\ V_p &= -u_p \sin \beta + v_p \cos \beta \\ \beta &= \tan^{-1} \left\{ A_r \frac{2\pi}{L_r} \cdot \cos \left(\frac{2\pi}{L_r} x_c' + \alpha \right) \right\} \end{aligned}$$

*** The derivation is expressed in the Appendix.

(144mm×26mm) in which particles are regarded to move two-dimensionally and the test section is 6m. The particles have relatively large size, e. g. above 500-micron diameter.

2. Rough Wall Model

In actual pneumatic conveying, we can scarcely get a completely smooth pipe. In particular, when a pipe the inside wall of which has a relatively large degree of roughness, such as a steel pipe, is used as a transport line, the roughness of wall is considered to be more controlling to the irregular bounce than the slight deformation of particle shape.

In this paper, the irregular bounce caused by the roughness is modelled as the following sine function, which is schematically described in Fig. 1,

$$y' = A_r \cdot \sin \left(\frac{2\pi}{L_r} x' + \alpha \right) \quad (1)$$

where α is the phase of roughness against the particle. The roughness of wall was assumed to have a uniform distribution. This assumption was introduced into the simulation in the following manner; the roughness of wall surface was assumed to have no correlation with the position of a particle approaching the wall and the phase of roughness, α , was treated as a random variable distributed uniformly over $[0, 2\pi]$. The reasons for introducing a random factor in this manner have been described in a previous paper³⁾.

In this model, if the contact point of a particle with the rough wall is specified, the bouncing phenomenon will be analysed as that of a spherical particle on the tangential plane at the contact point.

In this way the complex calculation of the bounce of a nonspherical particle as in the case of the ellipsoid bouncing model can be avoided. General solutions of the bounce of a spherical particle on a tangential plane are expressed as***

$$\text{if } \left| \frac{V_p^0}{U_p^0 + \frac{1}{2} d_p \omega_p^0} \right| \geq \frac{2}{7(1+e)\mu_k} \quad (\text{no-slip})$$

$$U_p' = \frac{5}{7} U_p^0 - \frac{1}{7} d_p \omega_p^0 \quad (2)$$

$$V_p' = -e V_p^0 \quad (3)$$

$$\omega_p' = \frac{2}{7} \omega_p^0 - \frac{10}{7} \frac{U_p^0}{d_p} \quad (4)$$

$$\text{and if } \left| \frac{V_p^0}{U_p^0 + \frac{1}{2} d_p \omega_p^0} \right| < \frac{2}{7(1+e)\mu_k} \quad (\text{slip})$$

$$U_p' = U_p^0 + \varepsilon_0 \cdot \mu_k (1+e) V_p^0 \quad (5)$$

$$V_p' = -e V_p^0 \quad (6)$$

$$\omega_p' = \omega_p^0 + \frac{5}{d_p} \cdot \varepsilon_0 \cdot \mu_k (1+e) V_p^0 \quad (7)$$

$$\text{where } \varepsilon_0 = \text{SIGN} \left(U_p^0 + \frac{1}{2} d_p \omega_p^0 \right) = \pm 1$$

For the two-dimensional motion of a particle in a gas stream, the same assumptions were used as in the ellipsoid bouncing model. Equations of particle motion in a gas stream were expressed as follows: for the x -direction,

Fig. 2 Effect of ω_p^0 on the distribution of (u_p', v_p') (glass beads, $d_p=1.0$ [mm], $A_r/d_p=1/20$, $L_r/d_p=10$, $e=0.97$, $\mu_k=0.4$)

$$\frac{du_p}{dt} = \frac{3}{4} \frac{\rho_a}{\rho_p + \chi \rho_a} \frac{C_D}{d_p} \cdot |u_a - u_p| \cdot (u_a - u_p) \quad (8)^*$$

and for the y -direction,

$$\begin{aligned} \frac{dv_p}{dt} = & -\frac{3}{4} \frac{\rho_a}{\rho_p + \chi \rho_a} \frac{C_D}{d_p} \cdot |v_p| \cdot v_p + \frac{\rho_a - \rho_p}{\rho_p + \chi \rho_a} g \\ & + \frac{3}{4} \frac{\rho_a}{\rho_p + \chi \rho_a} \frac{C_L}{d_p} (u_a - u_p)^2 \end{aligned} \quad (9)^*$$

3. Irregular Bounce Based on the Rough Wall Model

First, the bouncing characteristics of this model will be discussed. Fig. 2 shows the distribution of translational velocity after bounce, (u_p', v_p') , in the same expression as that in the ellipsoid model. It does not scatter at random and is expressed as a closed curve. Fig. 2 shows that if a 1.0 mm glass bead collides with the wall at an incident angle of 30° , having a velocity of 5 m/sec and an angular velocity of -6000 radian/sec, it rebounds having one of the translational velocities on curve ②. Fig. 3 (a), (b) and 4 show the cumulative distribution function of the apparent restitution coefficient which is defined as the ratio of the absolute value of normal component of particle velocity before bounce to that after bounce, $\bar{e}_y (=|v_p'/v_p^0|)$. These figures show that the probability of the event $\bar{e}_y > 1$ is quite large, even for a very small degree of roughness, A_r .

The probability $P(\bar{e}_y > 1)$ becomes large with increase of A_r and decrease of incident angle, θ_i , if the other condition remains the same. Fig. 4 shows that the probability $P(\bar{e}_y > 1)$ increases as the angular velocity, ω_p^0 , decreases, and this tendency differs a little from that of the ellipsoid bouncing model. Moreover, Fig. 5 shows the effect of ω_p^0 on the cumulative distribution of the difference between the reflection and the incident angle, $\Delta\theta$. This distribution pattern differs from the experiment of Ranz et al.⁴⁾ in which a normal distribution

Fig. 3 (a) Effect of A_r on the cumulative distribution function of $\bar{e}_y$, $F(\bar{e}_y)$

Fig. 3 (b) Effect of A_r on the cumulative distribution function of $\bar{e}_y$, $F(\bar{e}_y)$

Fig. 4 Effect of ω_p^0 on the cumulative distribution function of $\bar{e}_y$, $F(\bar{e}_y)$

was obtained**. As regards the influence of the cycle of roughness, L_r , in Eq.(1), the probability $P(\bar{e}_y > 1)$ increases as L_r decreases, though this figure is not shown here. The distribution of energy loss during bounce also has a narrow spread in spite of the wide distribution of u_p' , v_p' and ω_p' , as seen in the bouncing of ellipsoid.

Consequently, the characteristics of this rough wall model will be assumed to be almost identical with those of the preceding ellipsoid model, excepting the mechanism of exchange of rotational to translational energy, as seen in Figs. 2 and 4.

* The local air velocity, u_a , was assumed to satisfy the 1/7-th-power law and C_L was evaluated from the data of Tani⁶⁾ and Maccoll²⁾.

** The cause of this difference is unknown, but the following facts are considered to be responsible; the experiment of Ranz et al. was carried out in a three-dimensional field and the rotational velocity of the particle before collision was not taken into account.

Fig. 5 Effect of ω_p^0 on the cumulative distribution function of the difference between reflection and incident angle, $\Delta\theta$. (glass beads, $d_p=1.0$ [mm], $A_r/d_p=1/20$, $L_r/d_p=10$, $V=500$ [cm/sec], $\theta_i=10^\circ$, $e=0.97$, $\mu_k=0.4$)

Fig. 6 Flow chart of Monte Carlo simulation

4. Monte Carlo Simulation of the Motion of Particles in Two-Phase Flow

Monte Carlo simulation of the motion of particles in a two-dimensional horizontal pneumatic transport line was carried out under the same assumptions as for the preceding model. In an actual pneumatic transport process, there are various probabilistic factors which influence the motion of particles, such as the variety of particle size, the irregularities of particle shape and of wall surface of conduit, the probabilistic properties of initial conditions at the feed point and others. Under these circumstances, the actual process may not be simulated fully by a deterministic model. For this reason, the roughness was assumed to be distributed at random on the duct surface. That is, α in Eq. (1) was treated as

Fig. 7 Discussion of the number of trials in Monte Carlo simulation, N .

Fig. 8 Effect of X on the concentration distribution of particles

Fig. 9 Effect of A_r on the concentration distribution of particles at $X=450$

a random variable and then Monte Carlo method was applied in this simulation. The procedure of calculation is shown graphically in Fig. 6. The random variable α was generated by a multiplicative congruential method. The concentration distribution of particles in the duct was calculated from the distribution of residence time in a section in the direction of height.

The number of trials in Monte Carlo procedure was from 50 to 100, which was enough for convergence, as shown in Fig. 7.

Fig. 8 shows that the particles do not settle down at the bottom of the duct and the concentration distribution is maintained through a long distance from the feed point. Fig. 9 shows the effect of A_r on the concentration distribution when 1mm glass beads are conveyed at $\bar{u}_a=7$ m/sec. The effect of A_r on the profile of translational particle velocity and the rate of revolution are, respectively, illustrated in Figs. 10 and 11 in comparison with experimental results. With increasing A_r , the

Fig. 10 Effect of A_r on the profile of u_p at $X=500$ (The set of parameters is the same as Fig. 9.)

Fig. 11 Effect of A_r on the rate of revolution of particles (The set of parameters is the same as Fig. 9.)

concentration distribution becomes more uniform in the direction of height, and average values of u_p and ω_p decrease. When A_r/d_p is 1/50 to 1/80, that is, the degree of roughness is 20 to 12.5 microns, the calculated results agree with experiments fairly well.

The additional pressure drop* in two-phase flow, ΔP_s , also can be calculated by supposing that it is solely due to the kinetic energy lost at the collision on the wall. Fig. 12 shows the influence of A_r on the additional pressure drop for 1mm glass beads at $\bar{u}_a=7$ m/sec. It should be noted from this result that the additional pressure drop in gas-solid two-phase flow depends on the roughness of wall. This fact was observed experimentally in a previous paper¹⁾.

The influence of A_r on the motion of particle is shown in Fig. 13 in terms of the frequency of collision with the wall surface; the larger the degree of roughness, A_r , the more violently particles collide against the upper wall.

In general, by "hydraulically smooth" pipe is meant that the Blasius formula is valid for the frictional resistance of the pipe. According to Nikuradse⁵⁾ a rough pipe can be regarded as "hydraulically smooth" in the following range,

$$\frac{k \cdot v^*}{\nu} \leq 5 \quad (10)$$

* This is expressed as

$$\Delta P_s = \Delta P_T - \Delta P_a$$

where ΔP_T is the total pressure drop and ΔP_a is the pressure drop due to fluid friction.

Fig. 12 Effect of A_r on the additional pressure drop (The set of parameters is the same as Fig. 9.)

Fig. 13 (a) Effect of A_r on the frequencies of particle collisions with the upper wall at $m=1$ (The set of parameters is the same as Fig. 9.)

Fig. 13 (b) Effect of A_r on the frequencies of particle collisions with the lower wall at $m=1$ (The set of parameters is the same as Fig. 9.)

where k is the height of protrusion and in this case all protrusions are contained within the laminar sub-layer. As for the experiment in Fig. 12, since $v^*=40.8$ cm/sec and $\nu=0.147$ cm²/sec, k is evaluated as follows,

$$k \leq 5\nu/v^* = \frac{5 \times 0.147}{40.8} = 0.0184[\text{cm}] = 184[\mu]$$

In simulation, k is $2A_r$, namely 40 to 25 microns.

Therefore this rough wall can be called "hydraulically smooth".

The effect of the cycle, L_r , on the concentration distribution of particles is shown in Fig. 14.

The influences of particle diameter and air velocity

Fig. 14 Effect of L_r on the concentration distribution of particles at $X=500$

Fig. 15 Effect of d_p on the concentration distribution of particles at $X=500$

Fig. 16 (a) Effect of $\bar{u}_a$ on the concentration distribution of particles at $X=500$

Fig. 16 (b) Effect of $\bar{u}_a$ on the concentration distribution of particles at $X=450$
(glass beads, $d_p=1.0$ [mm], C_L : Maccoll's data, $A_r/d_p=1/50$, $L_r/d_p=10$)

Fig. 17 Effect of A_r on the profile of u_p when 0.5mm glass beads are conveyed
($\bar{u}_a=7$ [m/sec], $L_r/d_p=10$, C_L : Maccoll's data)

Fig. 18 Effect of A_r on the concentration distribution of particles at $X=500$
(polystyrene beads, $d_p=0.94$ [mm], $L_r/d_p=10$, $\bar{u}_a=7$ [m/sec], C_L : Maccoll's data)

Fig. 19 Effect of A_r on the profile of u_p when polystyrene beads are conveyed (The set of parameters is the same as Fig. 18.)

upon the concentration distribution are also shown in Figs. 15, 16 (a) and 16 (b), respectively.

Fig. 17 shows the influence of A_r on the profile of u_p in the case of 0.5mm glass beads.

For polystyrene beads, the calculated results are illustrated in Figs. 18 and 19 and compared with experiments in terms of concentration distribution and velocity profile of particles.

Consequently, in the case of gas solid two-phase flow, even a very small degree of roughness, such as "hydraulically smooth" protrusion, is considered to have a great influence upon the behaviour of particles. But the glass duct used in this experiment does not have such roughness. Nevertheless, the experimental results can be explained relatively well by the above rough wall

model. This is probably because the probabilistic factors and all uncertainties such as irregularities of particle shapes and sizes have all been thrown into the roughness of wall surface.

Compared with the ellipsoid model, the rough wall model has the weakness that the physical meanings of two parameters, A_r and L_r , are somewhat ambiguous.

On the other hand, the ellipsoid model has one parameter, η , which is the ratio of the major to the minor axis of an ellipsoid and corresponds to the measured value of deformation of the particles. The ellipsoid model is superior to the rough wall model in this respect, but it is inferior in that the bounce of an ellipsoid particle involves a fairly complicated calculation.

Generally the adequacy of these models depends on the case to be considered and it is difficult to decide which to take.

5. Conclusion

Irregular bouncing phenomenon due to the irregularities of conduit wall was simulated by the rough wall model, and the probability of the event $\bar{e}_y > 1$ was evaluated.

Monte Carlo simulation with an irregular bouncing model based on a rough wall could account for the mechanism of particle floating.

Appendix

Impulsive Motion of a Spherical Particle in Two-Dimensional Field

When a spherical particle having translational velocity components U_p^0 and V_p^0 , and an angular velocity ω_p^0 , as shown in Fig. 1 (c), equations of impulsive motion are expressed as,

$$M_p(U_p - U_p^0) = F \quad (11)$$

$$M_p(V_p - V_p^0) = R \quad (12)$$

$$M_p\left(\frac{1}{10}d_p^2\right)(\omega_p - \omega_p^0) = \frac{1}{2}d_p F \quad (13)$$

where M_p is the density of a particle.

The relative velocities of a contacting point of the particle against the wall are given as follows,

$$U_r = U_p + \frac{1}{2}d_p \cdot \omega_p \quad (14)$$

$$V_r = -V_p \quad (15)$$

and at the initial state, these are

$$U_r^0 = U_p^0 + \frac{1}{2}d_p \cdot \omega_p^0 \quad (16)$$

$$V_r^0 = -V_p^0 \quad (17)$$

Eliminating U_p , V_p , ω_p , U_p^0 , V_p^0 and ω_p^0 from Eqs. (11) to (17), the following relations are obtained.

$$U_r = U_r^0 + \frac{7}{2} \frac{F}{M_p} \quad (18)$$

$$V_r = V_r^0 - \frac{R}{M_p} \quad (19)$$

The normal component of impulsive force acting on the particle throughout the bouncing process, R' , is obtained from the following equation,

$$R' = (1 + e)R^* = (1 + e)V_r^0 M_p \quad (\text{from Eq. (19)}) \quad (20)$$

where R^* is the normal component of impulsive force acting on the particle from the moment of contact with the wall to that of $V_r = 0$. If the x -component of the impulsive force is to be caused by friction alone, the law of friction is expressed as,

①, ②, ⑤ and ⑥ correspond to Eqs. (2), (3) and (4).
③ and ④ correspond to Eqs. (5), (6) and (7).

Fig. 20 Examples of R-F diagrams for the bounce of spherical particle

$$\text{for the process of } U_r \neq 0, \quad \frac{dF}{dR} = -\varepsilon_0 \mu_k \quad (21)$$

$$\text{for the process of } U_r = 0, \quad \left| \frac{dF}{dR} \right| \leq \mu_s \quad (22)$$

$$\text{where } \varepsilon_0 = \text{SIGN}(U_r) = \pm 1 \quad (23)$$

The x -component of impulsive force after bounce, F' , is obtained from Eqs. (18), (19) and (20) and Eq. (21) or Eq. (22). The procedure of calculation is as follows; the line of Eq. (19) at $V_r = 0$ is drawn parallel to the F axis in a R - F plane as in Fig. 20. The line of Eq. (18) at $U_r = 0$ is parallel to the R axis, and if U_r^0 is positive this line lies in a negative field of ordinate, otherwise it lies in a positive field.

Then the value of F' corresponding to R' is obtained from the R - F diagram.

Consequently the translational and angular velocities after bounce (U_p' , V_p' , ω_p') can be calculated from the following equations,

$$U_p' = U_p^0 + \frac{F'}{M_p} \quad (24)$$

$$V_p' = V_p^0 + \frac{R'}{M_p} \quad (25)$$

$$\omega_p' = \omega_p^0 + \frac{5}{d_p} \frac{F'}{M_p} \quad (26)$$

The general solutions of a set of the above simultaneous equations are given by Eq. (2) to Eq. (7). On these equations, the judgment of slip or no-slip is due to the ratio of relative velocities of contacting point, that is, the tangent of incident angle.

Acknowledgement

The authors express their sincere thanks to Professor Siro Maeda for valuable suggestions and criticisms.

Numerical calculation was carried out on the high-speed digital computers NEAC 2200 of Tohoku University and HITAC 5020 of Tokyo University.

Nomenclature

A_r	= amplitude of roughness	[m]
C_D	= drag coefficient	[—]
C_L	= lift coefficient	[—]
d_p	= particle diameter	[m]
e	= coefficient of restitution	[—]
$\bar{e}_y$	= apparent restitution coefficient ($= v_p'/v_p^0 $)	[—]
F	= tangential component of impulsive force acting on the particle	[Kg·sec]
H	= a half of the duct height ($=0.013$)	[m]
k	= height of protrusion	[m]
L	= duct length	[m]

L_r	= cycle of roughness	[m]
m	= mass flow ratio	[—]
N	= number of Monte Carlo trials	[—]
n_i	= number of particles in a fraction of height divided into 7 sections	[—]
ΔP_s	= additional pressure drop	[Kg/m ²]
R	= normal component of impulsive force acting on the particle	[Kg·sec]
t	= time	[sec]
$u_a, \bar{u}_a$	= local and mean air velocities	[m/sec]
u_p, v_p	= x and y components of particle velocity	[m/sec]
U_p, V_p	= velocity components of particle in the tangential coordinates	[m/sec]
V	= particle speed before bounce ($=\sqrt{u_p^0{}^2 + v_p^0{}^2}$)	[m/sec]
v^*	= friction velocity	[m/sec]
x	= distance from feed point	[m]
X	= dimensionless distance from feed point ($=x/H$)	[—]
α	= phase of roughness	[radian]
ε_0	= coefficient ($=\text{SIGN}(U_p^0 + 0.5d_p\omega_p^0) = \pm 1$)	[—]
θ_i, θ_r	= incident and reflection angles	[degree]
μ_k, μ_s	= coefficients of kinetic and static friction	[—]
ν	= kinematic viscosity of gas	[m ² /sec]

ξ	= random variable with probability density function $f(\bar{\varepsilon}_y) (=dF(\bar{\varepsilon}_y)/d\bar{\varepsilon}_y)$	[—]
ρ_a, ρ_p	= air and particle densities	[Kg/m ³]
χ	= coefficient of virtual mass	[—]
ω_p	= angular velocity of particle	[radian/sec]

Superscript	
⁰	= before bounce
[']	= after bounce

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DE-ENTRAINMENT EFFICIENCY OF A SIEVE PLATE COLUMN*

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Studies were made of the de-entrainment efficiency of an 80mm-diameter sieve plate column for the steam-water system. Variables studied were superficial steam velocities from 22.2 to 111 cm/sec, reflux ratios from 0.1 to 3.0 and plate spacing from 10 to 40 cm. It was found that some of the droplets formed on the n -th tray and carried up through the $n+1$ -th tray at a ratio f_1 were carried up again through the $n+2$ -th tray at a considerably greater ratio f_2 , and some of these droplets carried up through the two trays were carried up again and again through the $n+3$ -th tray at a slightly greater ratio f_3 than f_2 , which seriously impaired the efficiency of the plate column. The maximum values of decontamination factors DF_1 , DF_2 , and DF_3 obtained were nearly 10^2 , 10^3 and 10^4 respectively.

Introduction

The phenomenon of entrainment occurs in most equipment where vapor or gas is generated from or passed through a liquid layer. Entrainment adversely affects the efficiency of equipment. Evaporators, absorption towers, distillation columns and catalyst chambers are examples of equipment in which entrainment occurs, causing serious contamination or loss of product.

Evaporation is the most effective general method for removal of radioactive contaminants from a solution. When a radioactive liquid waste is concentrated in an evaporator, however, radioactive liquid droplets are entrained in the vapor rising from the evaporator, which

impairs the decontamination efficiency of the evaporator. Decontamination factors between pot and distillate have been reported^{1,2)} to range from 10^4 at lower superficial vapor velocities up to 10^5 at higher velocities. These values are raised to from 10^6 to 10^7 after the distillate has passed through a cyclone separator, and finally to about 2×10^7 after passing through a glass-fiber-packed tower. The decontamination factors of the cyclone only have been also reported^{1,2)} to range from 2 to 10^3 . According to York^{1,6)} and Carpenter and Othmer³⁾, decontamination factors of a wire-mesh demister are 10^3 and from 5 to 10^3 , respectively.

The author has studied the decontamination, de-entrainment or separation efficiency of a sieve plate column demister and found that all of the entrained droplets are not captured by the liquid on a tray, but some of them pass through the tray with a ratio f , thus decreasing the efficiency of the column. Taking this phenomenon into consideration, the author investigated how the decontamination efficiency of a plate column was affected by

* Received on September 24, 1969
The 3rd Autumn Meeting of Soc. of Chem. Eng., Japan, October 14, 1969

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