POLSKA AKADEMIA NAUK
INSTYTUT MASZYN PRZEPŁYWOWYCH

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

89

WARSZAWA – POZNAŃ 1989
PAŃSTWOWE WYDAWNICTWO NAUKOWE

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

*

THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

REDAKCJA — EDITORIAL OFFICE

Instytut Maszyn Przepływowych PAN
ul. Gen. Józefa Fiszera 14, 80-952 Gdańsk, skr. pocztowa 621, tel. 41-12-71

ISBN 83-01-07072-2
ISSN 0079-3205

PAŃSTWOWE WYDAWNICTWO NAUKOWE - ODDZIAŁ W POZNANIU

Nakład 300+90 egz. Ark. wyd. 13,25. Ark. druk. 10,5. Papier offsetowy kl. IV, 71g.
B-1. Oddano do składania w kwietniu 1987 r. Podpisano do druku w marcu 1989 r.
Druk ukończono w grudniu 1989 r. Zam. 90/89 K-8/66
SKŁAD WYKONANO W ZAKŁADACH GRAFICZNYCH im. KEN W BYDGOSZCZY
DRUK ZAKŁAD POLIGRAFII WSP W ZIELONEJ GÓRZE

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH
1989 Zeszyt 89

MARIAN TRELA
Gdańsk

Deposition of Droplets in Two-Phase Dispersed Flow*

Turbulent deposition of droplets from two-phase dispersed flow onto the smooth wall of a vertical tube has been studied. A model is proposed which takes into account the difference between particle and eddy diffusivities as well as the stochastic nature of the phenomenon. The theory is tested against the data which cover a wide range of droplet size and Reynolds number. A quite satisfactory agreement has been found in all examined cases.

Numenclature

A, A_1 — constant coefficients,
a, a_1 — constant coefficients,
b — ratio of eddy diffusivities, $b = \varepsilon_p/\varepsilon_g$,
B — ratio of average to maximum concentration, $B = \bar{c}/c_c$,
c — concentration,
d — diameter,
D — coefficient defined in the text,
$E(\omega)$ — energy spectrum function,
k — mass transfer coefficient, $k = m_t/c$,
m — particle mass flux, exponent,
n, n_1, n_2 — exponents,
P, P_1, P_2 — probabilities,
R — ratio, $R = v_g/u^*$,
Re — duct Reynolds number, $Re = ud_t/\nu_g$,
s — stopping distance,
s^+ — dimensionless stopping distance, $s^+ = su^*/\nu_g$,
u^* — friction velocity, $u^* = (\tau_w/\varrho_g)^{1/2}$,
u — axial velocity,
v — y-directional velocity fluctuation,
y — distance from the wall,
y^+ — dimensionless distance, $y^+ = yu^*/\nu_g$,
ε_p, ε_g — particle and gas diffusivities,
ω — angular frequency,
μ — viscosity,
τ — shear stress,
ν — kinematic viscosity,
ϱ — density.

Subscripts:

c — center,
cr — characteristic,
o — initial,
g — gas,
p — particle (droplet),
t — turbulent, tube,
w — wall,
$\bar{\ }$ — mean.

1. Introduction

The determination of droplet (particle) deposition rates is of interest in many technical applications such as steam generators, spray cooling and other two-phase flow situations. A critical examination of the deposition data for wide range of

* This paper has been presented at the Colloquium EUROMECH 162 organized by the Institute of Fluid-Flow Machinery, Polish Academy of Sciences and the Technical University Karlsruhe in 1982.

particle size has been reported among others by McCoy and Hanratty [1]. They have presented the dimensionless deposition coefficient (velocity) $k/u^* = \dot{m}_t/\bar{c}u^*$ versus the dimensionless stopping distance s^+ (Fig. 1). The stopping distance s is defined as a distance a particle would travel through a stagnant fluid with an initial velocity u_0 under the action of a drag force alone. If the initial velocity is equal to the friction velocity u^* then the stopping distance

$$s = \frac{\varrho_p d_p^2 u^*}{18\mu_g} \tag{1}$$

and its dimensionless form

$$s^+ = \frac{su^*}{\nu_g} = \frac{\varrho_g \varrho_p d_p^2 u^{*2}}{18\mu_g^2}. \tag{2}$$

One may distinguish three different regimes of turbulent deposition in Fig. 1.

For particles in submicron range, $s^+ < 0.15$ (regime I) the process is controlled by Brownian diffusion and the major resistance to particles transport resides in the viscous boundary layer.

However, a particle size or stopping distance s^+ may be reached above which the inertia of the particles becomes very high. It means that the velocity given to the particles by turbulent eddies enhances the deposition rate abruptly. This is the second regime (II) termed the eddy diffusion-impaction regime. It occurs for the particles in the range $0.15 < s^+ < 20$.

As the particle size rises still further ($s^+ > 20$) the process becomes determined by

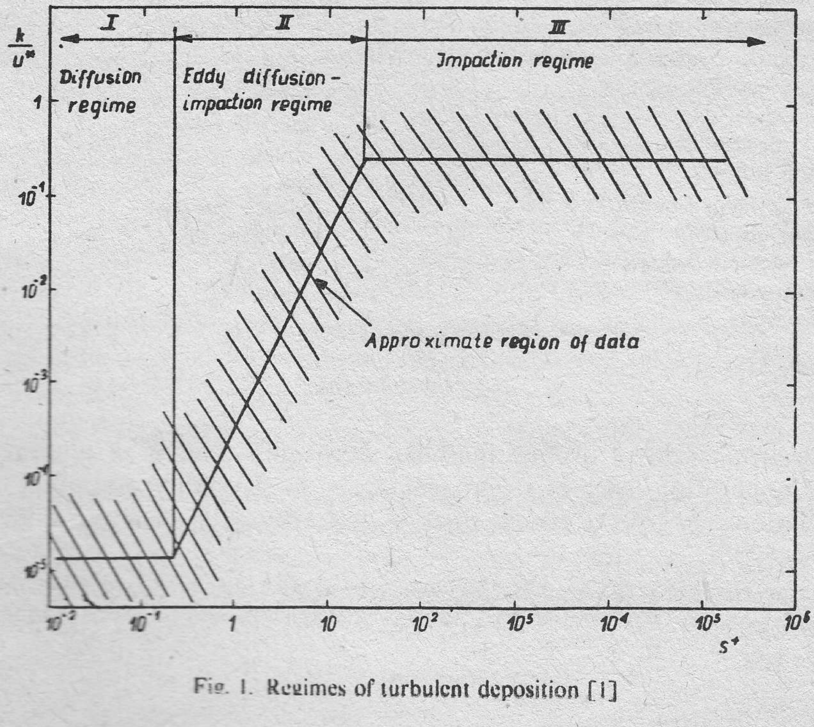

Fig. 1. Regimes of turbulent deposition [1]

the particle inertia. The particles can not attain the eddy velocity, which stops and then decreases the deposition rate. This is the impaction regime of deposition (III regime).

Most of the practical applications involving two-phase dispersed flow fall into II or III deposition regimes. A number of theoretical analyses exist for prediction of the deposition rates in these regimes e.g. [2, 3, 4, 5]. They are based on the observation that the deposition rate is controlled by two processes (Fig. 2):

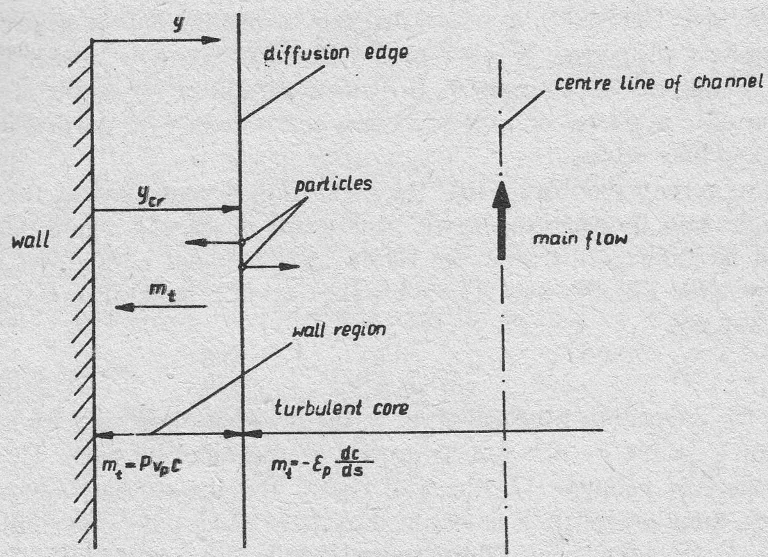

Fig. 2. Idealized model of particle deposition mode

a) diffusion of the particles in the turbulent core to a region near the wall,

b) penetration of this wall region by inertia coasting, called also „a free flight". This is due to the initial momentum imparted to particles by the fluid eddies at the edge of the turbulent core (diffusion edge).

The mentioned deposition models make usually use of the Fick's diffusion equation

$$m_t = -\varepsilon_p \frac{dc}{dy}, \tag{3}$$

which is integrated over the turbulent core with appropriate expressions for the particle eddy diffusivity and the thickness of the wall region. This approach suggests that the proper description of the particles behaviour in the core will give good results. This, however, is not the case. Due to the assumption used some of the models predict satisfactorily the deposition rate in the eddy diffusion-impaction regime and others in the impaction one. None of them can be successfully used for both regimes. It is purpose of this paper to present a deposition model which covers both regimes.

2. Analysis

The present model is concerned with particles which have the stopping distance s^+ in excess of 0.15. Its basic feature is the belief that the proper description of the behaviour of the particles at the diffusion edge and in the wall region is of key importance for the prediction the deposition rate. Therefore the main attention is focused on this region instead of the turbulent core, as was done in the former models.

The analysis is restricted to deposition from fully developed turbulent flow in a vertical channel. The concentration of droplets is small enough to neglect its effect on turbulent fluid properties. It is assumed that once the droplet strikes the surface there is no rebound or reentrainment. Brownian motion, electrostatic, Magnus and thermal forces are neglected and the process is controlled by the particle inertia and the intensity of fluid eddies.

The model retains the feature that the deposition is controlled by the turbulent diffusion in the bulk flow and the inertia penetration of the wall region. Thus for the bulk flow it is still regarded that the Fick's Law provides a valid description of particle dispersion. For the wall region the deposition rate is expressed in another way by the relation

$$m_t = P v_p c, \tag{4}$$

where P is the deposition probability, v_p is the initial particle velocity in the wall direction and c is the particle concentration at the diffusion edge. This formula reflects the particle behaviour in the wall region and the stochastic nature of the phenomenon. Simultaneously it is assumed that the thickness of the wall region is equal to the stopping distance s. This implies that the diffusion edge is dependent on particle, pipe and fluid properties. In this respect the model differs from others (e.g. [5—7]), where usually the constant thickness is used. The evaluation of the above relations will give the deposition coefficient k.

It has been almost generally assumed (e.g. [2, 4, 5]) that the particles reaching the diffusion edge should deposit on the wall. This is equivalent to the statement that the deposition probability P is equal to one. This, however, is not a realistic assumption since at this locus a particle has equal probability to move toward the wall or back into the turbulent core. Therefore in the present analysis is assumed that P is less than one and is given as

$$P = P_1 P_2, \tag{5}$$

where P_1 is the probability for the particle to get the velocity impulse toward the wall, P_2 is the probability to reach the wall due to it. Deposition in circular channels is controlled by the radial particle velocity fluctuation v_p, thus $P_1 = 0.5$. Determination of the probability P_2 is more complicated. Since is has been assumed that the particles are insensitive to the eddies for $y < y_{cr}$ (Fig. 2), P_2 is inversely proportional to the probability of particle collision with other particles during a "free flight". This in turn is proportional to the stopping distance and the particle concentration [8]. Therefore the probability P_2 may be expressed as a product of two functions

$$P_2 = f_1(s^+) f_2(\bar{c}). \tag{6}$$

In this paper the analysis is limited to the low droplet concentration and thus $f_2(\bar{c}) = 1$. For the evaluation of the function $f_1(s^+)$ two cases should be considered:

1. If a particle starts toward the wall from a point within the laminar or buffer sublayer then P_2 is near one. This results from a small distance from the wall and the ordered structure of the fluid motion in this region. Therefore it may be assumed that for $s^+ \leqslant s^+_{cr}$ $P_2 = 1$, where the characteristic value of the stopping distance s^+_{cr} is to be evaluated. The data of Liu and Agarwal [9] and McCoy and Hanratty [1] (Fig. 1) suggest the characteristic value to be $s^+_{cr} \simeq 20$, since for higher value of s^+ there is a qualitative change in the variation of the transfer coefficient k/u^*.

2. For the particles characterized by $s^+ > 20$ the probability decreases when the stopping distance increases, thus one may write the following relation

$$P_2 = a_1 s^{+m}, \tag{7}$$

where the coefficients a_1 and m are to be found.

The next problem in the analysis is the particle initial velocity v_p as imparted by gas velocity fluctuation at the diffusion edge. The connection between them was investigated by Tchen (Hinze [10]). The result of this theory is given below as

$$\frac{\varepsilon_p}{\varepsilon_g} = \frac{\bar{v}_p^2}{\bar{v}_g^2} = \frac{\int_0^\infty E_p(\omega)d\omega}{\int_0^\infty E_g(\omega)d\omega} = b. \tag{8}$$

Thus the particle initial velocity v_p may be written as the function of the gas velocity fluctuation v_g and particle inertia represented by coefficient b

$$v_p = v_g \sqrt{b}. \tag{9}$$

Based on the investigations of Comte-Bellot [11] on spectral energy distribution in a turbulent flow the coefficient b_c (at the channel axis) was calculated in [8], in the same way as was done in [12]. The result is shown in Fig. 3. The paper of Namie and Ueda [13] shows that the coefficient b is almost constant in the turbulent core and falls down rapidly in the wall region. It may be therefore well described by the power law relation

$$b = b_c(2y/d_t)^{1/n} \tag{10}$$

which is often used in the boundary layer theory for the approximate calculations [14]. The use of it is also justified in the light of the foregoing assumption that the behaviour of the particles in the bulk flow is of minor importance for the deposition rate. According to Hinze [10] the inertia coefficient b may be written, for the case $\varrho_p \gg \varrho_g$ as

$$b \simeq \frac{1}{1 + \frac{1}{18}\varrho_p \frac{d_p}{\mu_g \tau_L}}, \tag{11}$$

where τ_L is the Lagrangian integral time scale. It is mainly a function of the Reynolds number. With the aid of Fig. 3 the coefficient b_c may be thus approximated as

$$b_c = \frac{1}{1+\frac{1}{18}\varrho_p \frac{d_p^2}{\mu_g}\left[0.57\left(\frac{d_p}{d_{50}}\right)^{0.15} Re^{0.62}\right]}, \tag{12}$$

where $d_{50} = 50 \cdot 10^{-6}$ m.

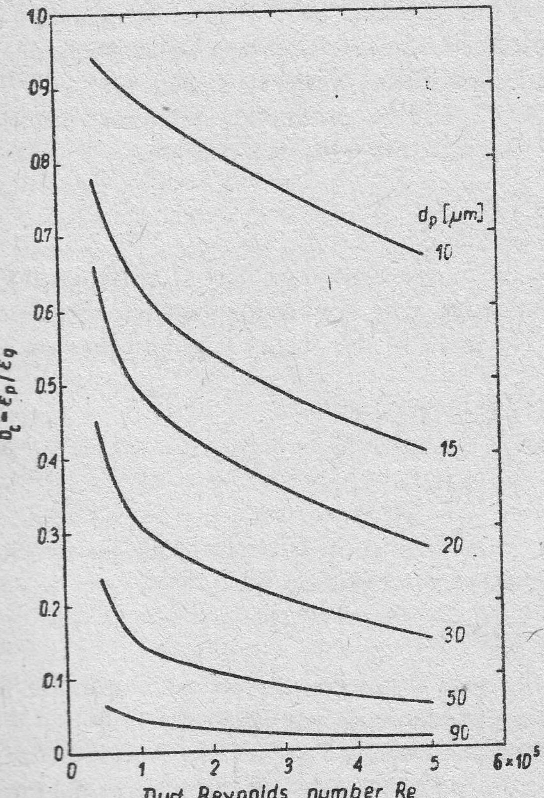

Fig. 3. Ratio of eddy diffusivities of water droplets and air at atmospheric pressure

A gas velocity fluctuation v_g in the turbulent flow was investigated among others by Laufer (Hinze [10]) and Lawn [15]. According to them the ratio $v_g/u^* = R$ varies rapidly in the wall region taking the value $R \simeq 0.7$ at $y^+ = 20$. Subsequently R rises slightly showing a certain maximum and then falls again to about 0.7 on the channel axis. Because the turbulent diffusivity coefficient of the gas varies near the wall as [10]

$$\frac{\varepsilon_g}{\nu_g} = Ay^{+n_1} \tag{13}$$

with the exponent $n_1 \simeq 2$, then a similar relation for the ratio R may be postulated

$$R = ay^{+n_1} \tag{14}$$

With the condition $R = 0.7$ at $y^+ = 20$ one obtains

$$R = 0.00175\, y^{+2} \tag{15}$$

for $y^+ \leqslant 20$. For the range $y^+ > 20$ the constant value $R = 0.7$ is assumed.

In order to determine the deposition rate m_t the droplets concentration should be known at one stopping distance from the wall. Beal [3] showed that in the turbulent core, i.e. for $s \leqslant y \leqslant d_t/2$, the concentration and velocity distributions are similar,

$$\frac{c}{c_c} \simeq \frac{u}{u_c} = \left(\frac{2y}{d_t}\right)^{1/n}. \tag{16}$$

He also pointed out that the power law relation of the droplet concentration is equivalent to the linear mass flux distribution m_t in this region, which has been frequently used (e.g. [5]). For the above distribution the ratio of the average — to — maximum concentration in the channel is given by [14]

$$\frac{\bar{c}}{c_c} = \frac{2n^2}{(n+1)(2n+1)} = B. \tag{17}$$

Taking into account eqs (4) to (17) with the condition that $y = s$ one obtains

$$m_t = \frac{PRu^*}{B}\left(\frac{2s}{d_t}\right)^{1.5/n} \sqrt{b_c}\,\bar{c} \tag{18}$$

from which at $n = 7$ the deposition coefficient is given by the relations:

$$\frac{k}{u^*} = 10.72\cdot 10^{-4} s^{+2}\left(\frac{2s}{d_t}\right)^{0.214} \sqrt{b_c} \tag{19}$$

for $s^+ \leqslant 20$ and

$$\frac{k}{u^*} = Ds^{+m}\left(\frac{2s}{d_t}\right)^{0.214} \sqrt{b_c} \tag{20}$$

for $s^+ > 20$. The coefficient D equals $D = 0.5a_1 R/B$.

If one assumes $P_2 = 1$ then according to the model $m = 0$ and $D = 0.43$. Thus equation (20) changes to the form

$$\frac{k}{u^*} = 0.43\left(\frac{2s}{d_t}\right)^{0.214} \sqrt{b_c}. \tag{21}$$

The accuracy of the proposed theory will be tested below by comparing the calculated results with the existing experimental data.

3. Comparison with experimental data

An extensive review of depositing data has been reported by McCoy and Hanratty [1]. Basing on it the authors suggested the correlation

$$\frac{k}{u^*} = 3.25\cdot 10^{-4} s^{+2} \tag{22}$$

for the eddy diffusion-impaction regime. This relationship shows the best fit to all the

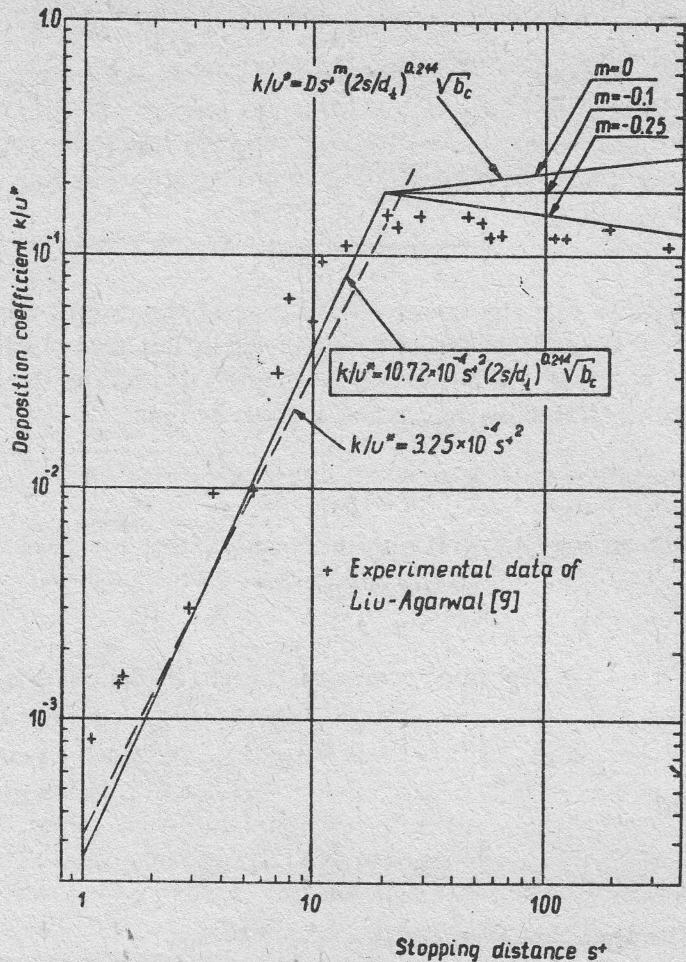

Fig. 4. Theoretical and experimental values of deposition coefficient in vertical pipes

data in this regime. Fig. 4 presents the comparison between the proposed theory, the above correlation and the data of Liu and Agarwal [9] known as the most reliable one. It is seen that the predicted values of k/u^* after eq. (19) almost coincide with those after eq. (22). A very good agreement with Liu and Agarwal data is also noted. The last one indicate that for $s^+ > 20$ the exponent m should be equal to about — 0.1 which gives $D = 0.579$. Thus eq. (2) changes to the form

$$\frac{k}{u^*} = 0.579 s^{+\,-0.1}\left(\frac{2s}{d_t}\right)^{0.214}\sqrt{b_c}. \qquad (23)$$

For larger particles the theory may be compared with the data of Cousins and Hewitt [16] who performed a measurement of water droplet deposition on two vertical tubes. They investigated the following range of parameters: the Reynolds number $Re = 37\,500$ to $56\,500$, the Sauter mean diameter $d_{32} = 40$ to 79 μm for the

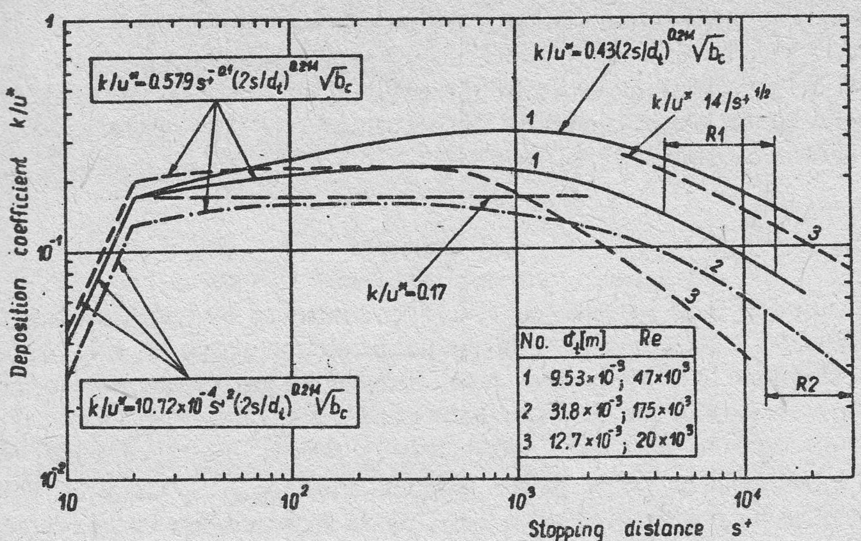

Fig. 5. Theoretical and experimental values of deposition coefficient in vertical pipes

tube $d_t = 9.35$ mm and $Re = 150\,000$ to $200\,000$, $d_{32} = 70$ to 110 um for the tube $d_t = 31.8$ mm. McCoy and Hanratty [1] presented the Cousins and Hewitt results in the form of the deposition coefficient getting $k/u^* \simeq 0.095$ for the smaller turbe and $k/u^* \simeq 0.068$ for the larger one. Since the effect of the Reynolds number is relatively small, the average Reynolds number were taken in the comparison with the theory. The results are shown in Fig. 5. The calculated values of the transfer coefficient k/u^* are practically constant within the range $20 < s^+ < 10^3$ and fall afterwards. Within the range designated in Fig. 5 as $R1$ and corresponding to the Cousins and Hewitt data on the smaller tube the mean value $\overline{k/u^*} \simeq 0.105$. For the less extensive set of measurements of deposition rates on the larger tube (R2) the calculated value is $\overline{k/u^*} \simeq 0.046$. It is seen that the agreement is quite satisfactory.

A further comparison was done with the data of Farmer et al. [17] obtained on a 12.7 mm vertical tube. They were recalculated by McCoy and Hanratty [1] and expressed in the form

$$\frac{k}{u^*} = \frac{A_1}{s^{+1/2}}. \tag{24}$$

The best fitting value of the coefficient A_1 was found to be 14. In this case the deposition coefficient after Farmer retains the same trend but takes the values about 100% higher than the predicted ones. This is partially due to the undeveloped droplet concentration profile during the experimental investigation.

In order to find the influence of the probability P_2 on the coefficient k/u^* its calculated values after eq. (21) are plotted in Fig. 5. It is seen that they are slightly higher than those predected by eq. (23). This is well understood in view of the presented theory.

Finally Fig. 5 shows the values of the transfer coefficient plotted after formula $k/u^* = 0.17$, recommended for practical use by McCoy and Hanratty [1]. It agrees well with the presented model within the range $20 < s^+ < 2000$. The model may be also applicable for the prediction of the deposition rate at the burnout conditions. This is shown in the paper [18].

4. Conclusions

Deposition of large particles ($s^+ > 0.15$) is controlled by two processes: a) turbulent diffusion in the core region, b) inertial projection across the wall region. The model is proposed in which both of these processes are particle-inertia dependent. It takes also into account the stochastic nature of the phenomenon. This model is very simple, showing simultaneously a satisfactory agreement with experimental data for a very wide range of values of the stopping distance s^+. It may be therefore recommended for practical use when a two-phase dispersed flow is considered.

Received the Editor at February 1984.

References

[1] D. D. McCoy, T. I. Hanratty, *Rate of deposition of droplet in annular two-phase flow*. Int. J. Multiphase Flow 3, 319-331, 1977.

[2] S. K. Friedlander, H. F. Johnstone, *Deposition of suspending particles from turbulent gas streams*. Ind. Engng. Chem. 49, 1151—1156, 1957.

[3] S. K. Beal, *Deposition of particles in turbulent flow on channel or pipe walls*. Nucl. Sci. Engng 40, 1—11, 1970.

[4] L. J. Forney, L. A. Spielman, *Deposition of coarse aerosols from turbulent flow*. Aerosol Science 5, 257—271, 1974.

[5] E. N. Ganic, K. Mastanaiah, *Investigation of droplet deposition from a turbulent gas stream*. Int. J. Multiphase Flow 7, 401—422, 1981.

[6] P. Hutchinson, G. F. Hewitt, A. E. Dukler, *Deposition of liquid or solid dispersions from turbulent gas streams, a stochastic model*. Chem. Engng. Sci. 26, 419—439, 1971.

[7] M. W. Reeks, G. Skyrme, *The dependence of particle deposition velocity on particle inertia in turbulent pipe flow*. J. Aerosol Sci. 7, 485—495, 1976.

[8] M. Trela, *Deposition of droplets from turbulent stream*. Wärme und Stoffübertragung 16, 161—168, 1982.

[9] Y. H. Liu, J. K. Agarwal, *Experimental observation of aerosol deposition in turbulent flow*. Aerosol Sci. 5, 145—155, 1974.

[10] I. O. Hinze, *Turbulence*. McGraw Hill Co, New York, 1975.

[11] G. Comte-Bellot, *Ecoulement turbulent entre deux parois paralleles*. Pub. Sci. et Tech. du Ministre del'Air, No 418, 1965.

[12] P. O. Rouhiainen, J. W. Stachiewicz, *On the deposition of small particles from turbulent streams*. Trans. ASME J. Heat Transfer 92, 169—177, 1970.

[13] S. Namie, T. Ueda, *Droplet transfer in two-phase annular mist flow*. Bull. ISME 16, 752—764, 1973.

[14] H. Schlichting, *Boundary layer theory*. McGraw Hill Co., New York, 1955.

[15] C. I. Lawn, *The determination of the rate of dissipation in turbulent pipe flow*. J. Fluid Mechanics 48, 477—506, 1971.

[16] L. B. Cousins, G. F. Hewitt, *Liquid phase mass transfer in annular two-phase flow, droplet deposition and liquid entrainment*. AERE R 5657, 1968.
[17] R. Farmer, P. Griffith, W. M. Rohsenow, *Liquid droplet deposition in two-phase flow*. Trans. ASME J. Heat Transfer 92, 587—594, 1970.
[18] M. Trela, *Heat and mass transfer in two-phase dispersed flow* (in Polish). Zeszyty Naukowe IMP PAN, No 154/1069/83.

Separacja kropel w przepływie dyspersyjnym

Streszczenie

W pracy rozważano zagadnienie separacji kropel (cząstek) z turbulentnego przepływu gazu na ścianki kanału. Intensywność tego zjawiska zależy od bezwładności kropel, którą reprezentuje wielkość zwana drogą hamowania s^+. Dotyczy to szczególnie kropel, dla których $s^+ > 0,15$, a więc kropel występujących najczęściej w przepływie dwufazowym o strukturze dyspersyjnej (mgłowej). Dla takich kropel przedstawiono w pracy model separacji. Opiera się on na spostrzeżeniu, że proces separacji kontrolowany jest przez turbulentną dyfuzję cząstek w jądrze przepływu, inercyjną penetrację cząstek przez obszar przyległy do ścianki. Gęstość strumienia cząstek w jądrze przepływu opisuje równanie (3), natomiast w obszarze przyściennym zależność (4), która uwzględnia stochastyczny charakter zjawiska. Na podstawie teorii przepływów turbulentnych obliczono prędkość początkową kropel oraz ich koncentrację w obszarze przyściennym. Doprowadziło to w konsekwencji do zależności (19) i (23), określających wielkość współczynnika separacji dla kropel spełniających warunek $s^+ > 0,15$.

Model ten skonfrontowano z badaniami eksperymentalnymi dla szeregu przypadków, uzyskując zadowalającą zgodność.

Сепарация капель в дисперсионном течении

Резюме

В работе рассмотрен вопрос сепарации капель (частиц) из турбулентного течения газа на стенки канала. Интенсивность этого явления зависит от инерции капель, которую определяет величина называемая путем торможения S^+. Это относится особенно к каплям, для которых $S^+ > 0,15$, т.е. капель чаще всего выступающих в двухфазном течении, характеризующимся дисперсионной (туманной) структурой. Для таких капель в работе представлена модель сепарации. Основывается она на наблюдении, что процесс сепарации контролируется турбулентной диффузией частиц в ядре течения, инерционным проникновением частиц через зону смежную к стенке. Плотность потока частиц в ядре течения описывается уравнением (3), а в пристенной зоне зависимостью (4), которая учитывает стохастический характер явления. На основе теории турбулентных течений вычислены начальная скорость капель и их концентрация в пристенной зоне. Это привело в последствии к зависимостям (19) и (23), определяющим величину коэффициента сепарации для капель соблюдающих условие $S^+ > 0,15$.

Эта модель сопоставлена с экспериментальными исследованиями для ряда случаев. Достигнута удовлетворяющая сходимость.