Int. J. Heat Mass Transfer. Vol. 14, pp. 337–351. Pergamon Press 1971. Printed in Great Britain

HEAT AND MASS TRANSFER BETWEEN GAS AND GRANULAR MATERIAL—PART III*

Z. F. CHUKHANOV
Krzhizhanovsky Power Institute, Moscow, U.S.S.R.

(*Received* 28 *August* 1968)

Аннотация—Рассмотрены процессы переноса тепла и вещества в газовзвеси (от газа к частицам) и установлены основные факторы, влияющие на их интенсивность. Показано, что при быстром смешении частиц и газа, процессы переноса в газовзвеси мелких частиц протекают с весьма высокой интенсивностью, возрастающей при увеличении концентрации твердых частиц в газовзвеси. Установлено, что при малых значениях *Re* торможения процесса переноса за счет стесненности движения в газовзвеси мелких частиц не может быть. Время нагрева газа (частиц) в условиях "гомогенизированной" (равномерно перемешанной) газовзвеси может быть доведено до тысячных и десятитысячных долей секунды. Основным фактором, тормозящим процесс в практических условиях является медленное и неудовлетворительное смешение газа и частиц. Этот же фактор затрудняет получение точных экспериментальных данных при исследовании процессов переноса в газовзвеси.

1. INFLUENCE OF CONCENTRATION OF γ_v OF SOLID PARTICLES IN GASEOUS SUSPENSION UPON HEAT AND MASS TRANSFER

IT HAS already been mentioned that the volumetric concentration γ_v is of great importance in increasing the active surface available for heat and mass transfer [see equation (19), Part II]. In some cases the increase in γ_v is used to intensify a heat transfer process per unit volume but its main task is to increase the amount of heat supplied per 1 m^3 of gaseous suspension. In many cases (in heat exchangers and reactors) this is the only possible method for the supply of large quantities of heat per 1 m^3 of active volume.

The rate of a process in gaseous suspension is increased by decreasing the size of particles [see equation (19), Part II] but the increase in the amount of heat supplied at a prescribed temperature drop may be achieved only by increasing γ_v (often up to values of 10^{-3}–10^{-1} m^3 per 1 m^3 of gaseous suspension) and the smaller the practically feasible temperature drop Δt of a "source", the greater should γ_v be.

As an illustration it may be mentioned that for pyrolysis of hydrocarbons or even more for balancing the heat requirements of the endothermic reactions in the manufacture of water gas, the necessary concentrations of a "solid heat carrier" are tens and even hundreds of kg per 1 kg cf reagent, which corresponds to

$$\gamma_v \sim 5{\cdot}10^{-3} \text{ to } 10^{-1}.$$

This as well as other works [3, 7, 17, etc] convincingly confirm the significance of the problem of the influence of γ_v upon the hydrodynamics and the heat and mass transfer in gaseous suspension.

In Fig. 9 is presented the chart from [3] for the effect of the concentration γ_v upon the transfer rate. From Fig. 9 it follows that starting from $\gamma_v = 3{\cdot}5^{\cdot}10^{-4}$, i.e. from 0·35 litre of solid particles per 1 m^3 of gaseous suspension, a

* The numbering of formulae, references and figures is continuous for Parts II and III.

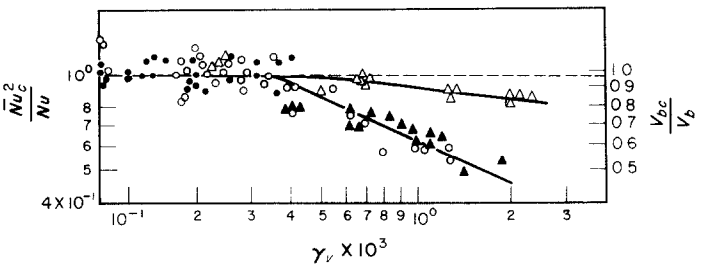

FIG. 9. Effect of concentration upon heat transfer in gaseous suspension from data of different authors.

reduction of heat and mass transfer is observed, which already at $\gamma_v = 1{\cdot}6 \cdot 10^{-3}$ (1·6 litre per 1 m^3) produces a twofold decrease in Nu under otherwise equal conditions.

Such an influence of the compression in particle movement ("squeezing") due to the effect of adjacent particles should already at very small concentrations γ_v (about two litres per 1 m^3 of gaseous suspension) completely eliminate the whole intensification achieved in gaseous suspension, as compared to fixed particles (see Fig. 8, Part II).

In Fig. 4 are presented charts showing the dynamics of cooling of coarse metal spheres ($d \sim 12$–30 mm) in air flow. As is seen from Fig. 4 the time of cooling of these spheres is several minutes, and in practice such coarse particles in cocurrent gaseous suspension cannot be used since the volume of a heater (heat exchanger) with gaseous suspension will be extremely large.

As will be seen below, the dynamics of heating (cooling) of spheres and particles of different configuration changes when passing to finer particles.

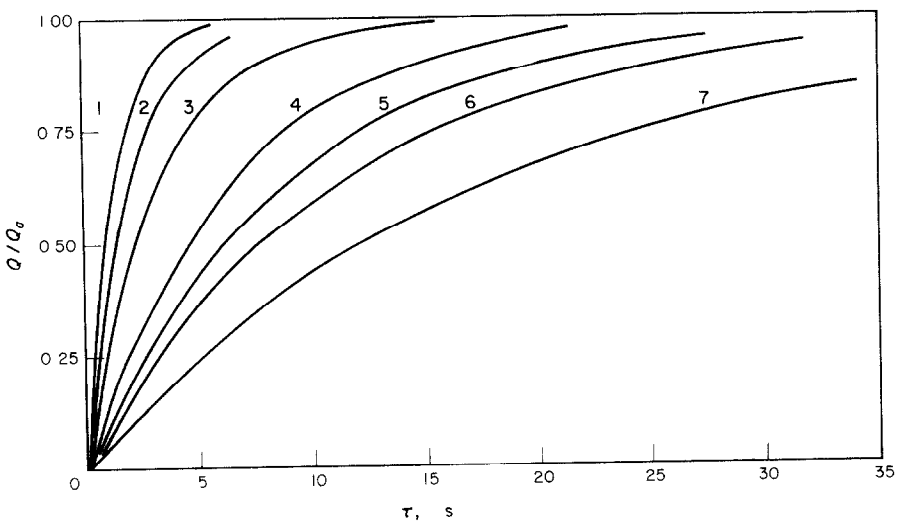

FIG. 10. Dynamics of gas heating of particles: 1—$d = 1{\cdot}0$ mm, $Nu = 0{\cdot}2 \cdot Re^{0{\cdot}82}$; 2—$d = 1{\cdot}0$ mm, $Nu = 0{\cdot}55 \cdot Re^{0{\cdot}5}$; 3—$d = 4{\cdot}0$ mm, $Nu = 0{\cdot}2 \cdot Re^{0{\cdot}82}$; 4—$d = 1{\cdot}0$ mm, $\gamma_v = 0{\cdot}01$ [with inclusion of γ_v according to equation (21)]; 5—$d = 4{\cdot}0$ mm, $\gamma_v = 0{\cdot}002$ [with inclusion of γ_v according to equation (21)]; 6—$d = 4{\cdot}0$ mm, $Nu = 0{\cdot}55 \cdot Re^{0{\cdot}5}$; 7—$d = 4{\cdot}0$ mm, $\gamma_v = 0{\cdot}01$ [with inclusion of the effect of γ_v according to equation (21)].

In Figs. 10 and 11 are presented the curves for the dynamics of heating of coke particles of different size in a hot gas. The curves are calculated from equation (4) (see Part II) where Nu for individual particles as well as for gaseous suspension [2] (see Part II) are determined from dimensionless equations (5)–(7)

$$Nu = 0{\cdot}20 \,.\, Re^{0{\cdot}82} \tag{20}$$

In a more general case, considering the effect of γ_v, we have

$$\tau(Q/Q_a) = -1380 \,.\, C_s\gamma_s \,.\, \frac{d}{\alpha} \log(1 - Q/Q_a) \times F(\gamma_v, C_s, \gamma_s, C_g, \gamma_g) \tag{22}$$

$$\tau(Q/Q_a) = -1380 \,.\, C_s \,.\, \gamma_s \,.\, \frac{d}{\alpha} \log(1 - Q/Q_a) \times \frac{C_g \,.\, \gamma_g(1 - \gamma_v)}{C_g \,.\, \gamma_g(1 - \gamma_v) + C_g \,.\, \gamma_g \,.\, \gamma_v}. \tag{23}$$

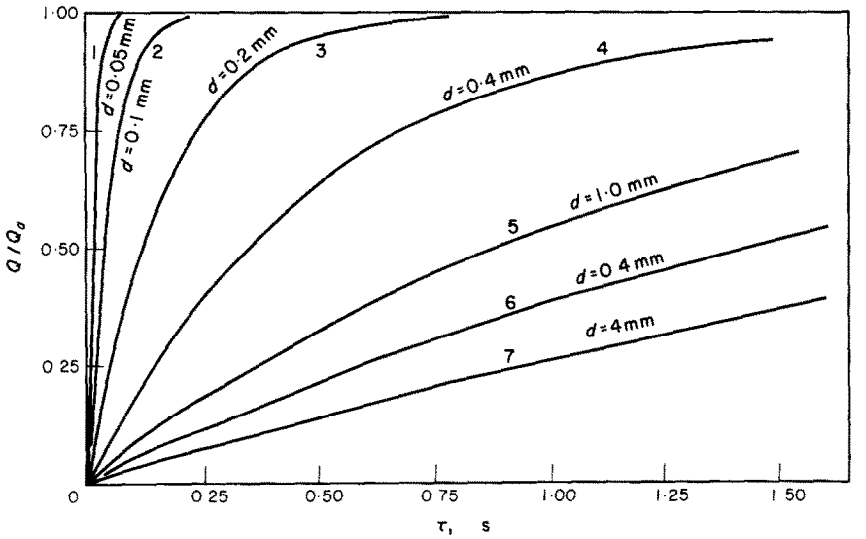

FIG. 11. Dynamics of gas heating of fine particles 1, 2, 3, 4—according to equation (7); 5—with inclusion of the effect of γ_v according to equation (21); 6, 7—according to equation (20).

For comparison, Figs. 10 and 11 also contain curves plotted according to the equation

$$Nu = 0{\cdot}006 \,.\, Re^{0{\cdot}8} \,\gamma_v^{-0{\cdot}43} \tag{21}$$

which takes into account the effect of concentration of the gas suspension (see Fig. 9) according to equation (21).

Equation (4), with the aid of which the time of heating of individual fixed particles (at $Bi < 0{\cdot}1$) is calculated, is also valid to calculate the time of heating of particles in gaseous suspension provided that $C_s \,.\, \gamma_s$ is small in comparison with $C_g \,.\, (1 - \gamma_v)$.

The times of heating calculated from equations (4), Part II, and (23) coincide when $C_s \,.\, \gamma_s \,.\, \gamma_v$ is small in comparison to $C_g \,.\, \gamma_g \,.\, (1 - \gamma_v)$ since the gas temperature during heating of solid particles changes slightly and the particles assume the temperature of the gas. Under real conditions the time of heating of particles decreases due to the large temperature difference between gas and particles.

The higher the concentration γ_v, the quicker the particles are heated up to a final temperature but, at the same time, the lower is the temperature of their heating and the less heat they

receive from the gas. The same is observed with cooling of hot solid particles by a cold gas.

As is seen from equation (23) when $C_s \approx C_g$ and $\gamma_s/\gamma_g = 10^3$ the time of heating of particles at $\gamma_{v_1} = 10^{-4}$ and $\gamma_{v_2} = 10^{-1}$ will decrease

$$\frac{(1-\gamma_{v_1})(1-\gamma_{v_2}+10^3\gamma_{v_2})}{(1-\gamma_{v_1}+10^3.\gamma_{v_2})(1-\gamma_{v_2})} = \frac{1-0{\cdot}1+100}{(1+0{\cdot}1)(1-0{\cdot}1)} \approx 100 \text{ times}$$

if, of course, the intensity of a process, characterized by a value of z, remains constant.

In Fig. 12 curve I represents the change (decrease) in time of heating of particles (up to a definite Q/Q_a) as a function of γ_v due to an increase in the temperature gradient between a gas and the particles. As is seen from Fig. 12, the time of heating should greatly decrease with an increase in γ_v and, especially, when $\gamma_v > 3.10^{-4}$.

In order to have an idea about the absolute time of heating of different particles, consider Figs. 10 and 11.

Coarse particles (about 4 mm in size) need more than 10 s for heating (up to $Q/Q_a \approx 0{\cdot}95$); particles 1 mm in size are heated in a gaseous suspension considerably quicker: 4 s with a turbulent boundary layer and 6 s with a laminar boundary layer.

Deceleration due to the increase in γ_v corresponding to Fig. 9 and equation (21) according to Z. P. Gorbis, sharply decreases the rate of heating of particles in gaseous suspension (Figs. 10 and 11). For example, particles of 1 mm size at $\gamma_v = 1{\cdot}6$–$2{\cdot}0$ litres per 1 m^3 of gaseous suspension ($\gamma_v = 1{\cdot}6.10^3$) are heated approximately at the same rate as coarse particles ($\sim$4 mm) without reduction due to compression effect in particle motion.

As is seen from Fig. 11, the fine particles are heated very quickly, even at small values of *Nu*, which are obtained as a result of small relative velocities of fine particles in a gas. Particles of 100 μ in size are heated (up to $Q/Q_a \approx 0{\cdot}95$) in 0·15 s and those of (50 μ, in 0·05 s. Such a high rate of heating allows to design compact, high intensity, heaters and reactors working with gaseous suspension.

It should be taken into account that according to equation (23) the time of heating of particles in gaseous suspension decreases with an increase in γ_v. This possible decrease in the time with a change in γ_v is shown in Fig. 12, curve I.

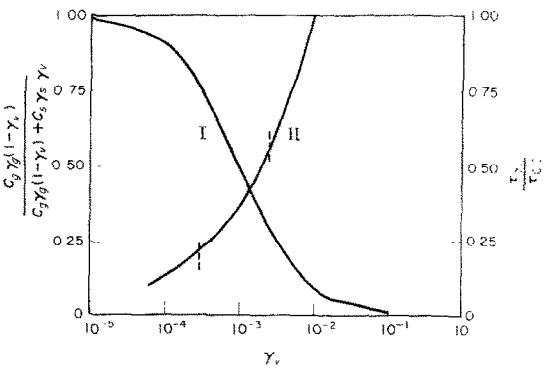

FIG. 12 Effect of concentration of gaseous suspension γ_v upon time of gas heating of particles I—due to increase in grad T, equation (23); II—due to squeezed motion of particles according to Z. P. Gorbis

Due to the increase in grad T, a noticeable change in τ_{fil} is already observed* at concentration $\gamma_v = 10^{-4}$ when $\tau_{fil} = 0{\cdot}9\tau$. At $\gamma_v = 3{\cdot}5.10^{-4}$ it already decreases down to $0{\cdot}75\tau$ (when the gas temperature varies). With a further increase in γ_v and absence of reduction due to the compression effect in the motion of particles, the actual time of heating of particles τ_{ac} greatly decreases, respectively achieving $0{\cdot}5\tau$ at $\gamma_v = 10^{-3}$, 0·09 at $\gamma_v = 10^{-2}$ and approximately 0·01 τ at $\gamma_v = 10^{-1}$. For particles 50 μ in size the time of heating is about 0·004 s at $\gamma_v = 0{\cdot}01$ and 0·0004 s at $\gamma_v = 0{\cdot}1$.

It is characteristic that in this case even particles of 200 μ in size at $\gamma_v = 10^{-3}$, 10^{-2} and 10^{-1} will get heated in 0·25, 0·09 and 0·005 s, respectively.

* Under the above conditions $C_g = C_s$; $\gamma_s/\gamma_g = 10^3$.

In Fig. 12 the vertical dotted lines show the limits of γ_v, for which equation (21) is valid, according to Fig. 9 and [3].

Curve II (Fig. 12) is plotted in accordance with equation (21). Curve II [3] characterizes the relative increase in the time of heating of particles due to acceleration of particles in gaseous suspension; the rate of heating at $\gamma_v = 0{\cdot}01$ is taken as the unit rate.

The comparison of curves I and II shows that if curve II correctly reflected the slowing down of a transfer process caused by the effect of compression of particle movement (squeezing) in gaseous suspension, then the improvement obtained by an increase in grad T γ_v would vanish with an increase in γ_v.

The aforesaid shows the significance of the problem on reduction in heat and mass transfer rates when the gaseous suspension concentration γ_v is increased.

Let us try to elucidate the essence of the transfer process mechanism under interaction between solid particles and a gas.

First of all, let us visualize the significance of concentrations of gaseous suspension γ_v within a range 10^{-5}–10^{-2}. At concentrations 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} in one cubic meter "box", with side 1 m long, spheres 0·01; 0·1; 1·0 and 10 litres in volume are respectively located at the centre.

Obviously, the diameters of these spheres will be 27, 58, 124 and 270 mm, respectively. For any gaseous suspension the dimensionless distance between spheres (particles)

$$S/d \approx \left(\frac{\pi}{6 \cdot \gamma_v}\right)^{\frac{1}{3}} = 0{\cdot}81 \cdot \gamma_v^{-1/3} \qquad (24)$$

is 37; 17·4; 8·1 and 3·7, respectively.

It is not difficult to see that for concentrations γ_v from 10^{-5} to 10^{-3} the distances between particles are very large. Under these conditions the noticeable effect of spheres upon the rate of transfer processes due to the squeezing effect in the motion of particles (particularly at the expense of getting to the wake) is not expected to occur. This conclusion is also confirmed by the fact that at $\gamma_v = 10^5 + 10^3$ the terminal falling velocity of particles v_b depending on concentration (Fig. 9) remains constant.

The experimental investigations, in which the decelerating effect of concentration at $\gamma_v < 10^{-3}$ is observed, are undoubtedly incorrect. In connection with this, note that the greatest distortions are due to rapid mixing of a gas and solid particles and maintenance of a homogeneous gaseous suspension in the whole test volume. The invalidity of the curve in Fig. 9 and equation (21) is confirmed by numerous investigations and, particularly, by the fact that in some experimental works [16] the effect of γ_v over the above range is not discovered.

There is also one largely decisive fact, which is very important for the analysis of the problem in question. Heat and mass transfer in gaseous suspension with fine particles, which move in a gas due to gravitational forces, is determined solely by molecular processes and, as is known, is described by a strict theoretical "limiting" equation (5), Part II.

Under these conditions the mutual interaction of solid particles in gaseous suspension which slows down transfer processes due to "squeezing" is completely absent at any γ_v. The approach of particles in this limiting case will intensify transfer, as was shown for a packed bed ($\gamma_v = 0{\cdot}5$), thus increasing Nu up to 4–5 [1], Part II. However, this intensification is clearly seen only at very high concentrations of gaseous suspension ($\gamma_v = 2 \cdot 10^{-1}$).

The slowing down of heat and mass transfer with a strong increase in γ_v is also possible in the limiting regime ($Nu = 2$) [1], Part II. The explanation of this phenomenon is the "heat dissipation" caused by intensification of molecular heat conduction along the flow of gaseous suspension as a result of the increase in the gradients of temperatures (concentrations). This effect is inevitably observed in the case of fine particles and $\gamma_v > 10^{-1}$ when the extent of the region of sharp drops of temperatures and concentrations is limited by the values of order of 10^{-3} m.

Thus, for fine particles at $Nu \approx 2$ the decelerating effect of concentration γ_v upon heat transfer is eliminated for all possible values of γ_v.

However, at $\gamma_v > 10^{-1}$ the intensifying effect of γ_v upon heat transfer (due to an increase in Nu) and the decelerating effect of γ_v upon heat transfer (due to heat dissipation along the flow of gaseous suspension) are revealed. Both these effects may be taken into account in concrete calculations with sufficient degree of accuracy [1], Part II.

However, at $Nu = 2$ the hydrodynamic conditions in gaseous suspension will not influence the rate of transfer processes up to very high values of γ_v, including fluidized and packed beds of solid particles but for more coarse particles when $Nu \neq$ const. this problem remains in force and, for the formulation of a procedure, it is necessary to establish the regions of the practically noticeable effect of this factor.

The interesting and very peculiar situation appears when considering the problem of the decreasing effect of the concentration γ_v of a solid phase on the heat transfer rate in gaseous suspension. On one hand, at low concentrations 10^{-5}–10^{-3} this decreasing effect is small because the solid particles are located far away from each other and their mutual effect is negligible and, on the other hand, in a packed bed, i.e. at γ_v having a maximum value this effect is also small, which is established by the fact that the measured rate of transfer is high [1], Part II.

If we add that at $Nu \approx$ const. the squeezing effect of particles does not slow down a process, then the peculiarity and complexity of the effect of γ_v will be especially obvious.

We have already mentioned that the slightest destruction of a packed bed greatly influences the hydrodynamics and the heat and mass transfer rate. It may now be said with certainty that at $\gamma_v = 3$–$5 \cdot 10^{-1}$ the effect of γ_v upon the transfer rate is very great and therefore the upper limit of the effect of γ_v is sufficiently obvious.

It should be noted that for substantiated estimation of the lower limit of γ_v when the squeezing effect of particles becomes pronounced there are unfortunately at present no reliable experimental data on gaseous suspension of high concentrations of rather coarse particles. However, for such estimation it is possible to use the data on heat transfer in bundles of cylindrical tubes for which, as we have already established, the character of flow past and transfer rate into are similar to flow and heat transfer of a gas with spherical particles and particles of other configuration.

In Fig. 13 are presented the experimental results [6], Part II on heat transfer of a gas flow with tube bundles* having a different pitch (S_2/d) along and (S_1/d) across the flow. As seen from Fig. 13, at $Re = 2 \cdot 10^3$–$40 \cdot 10^3$ all the points with a different tube pitch along the depth of a bundle lie on a single curve. The transfer intensity remained constant (with respect to Nu) for different tube pitches (S_1/d from 1·25 to 3·0) in a bundle across the flow.

As the increase in S_1/d changes the gas flow velocity, then the constancy of Nu denotes deceleration due to the squeezed motion of particles, which is approximately equal to the intensification to be obtained due to the increase in the velocity caused by a decrease in a free flow cross-section.

The absence of any noticeable effect of S_2/d, which is of great importance, is confirmed by numerous investigations, including [17], in which S_2/d varies over a wide range of bundles with staggered and in-line arrangement.

With a change in S_1/d($S_1/d = S_2/d$) from 1·25 to 4 the volume "concentration.. of tubes varied from 0·5 to 0·05. The fact that the volume concentration varied over such a wide range does not essentially affect the heat transfer rate shows that γ_v in gaseous suspension may hardly affect this rate when $\gamma_v < 0{\cdot}2$–$0{\cdot}3$, which corresponds to $S/d = 1{\cdot}4$ and 1·2 respectively.

* With a staggered arrangement of tubes similar to a "homogeneous" particle distribution in a gaseous suspension.

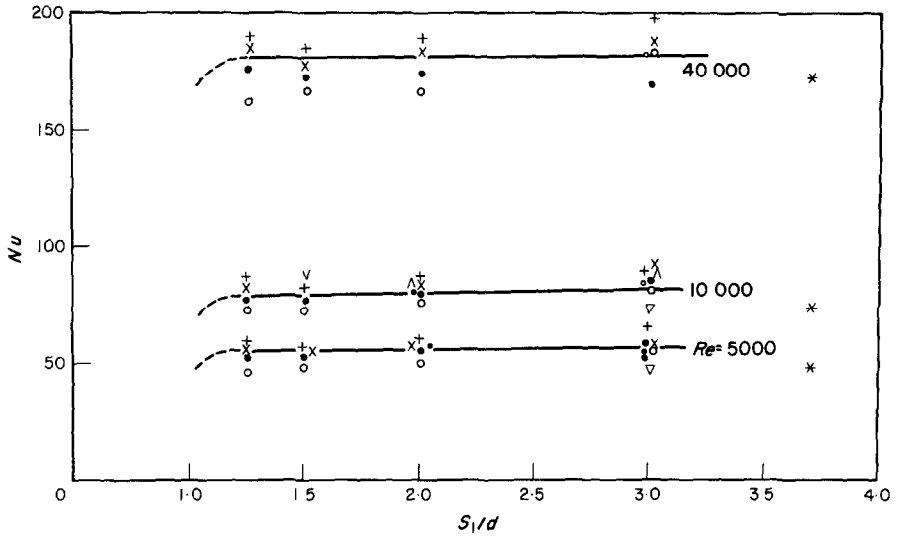

FIG. 13. Effect of squeezed motion of gas upon rate of heat transfer with staggered arrangement of a bundle of cylindrical tubes: S_1/d—pitch across flow; S_2/d—pitch along flow.

With in-line arrangement of tubes (rectangular pitch) the high volume "concentration" of tubes in a bundle should be extremely pronounced since the subsequent row of tubes is always within the "wake" of the flow around the preceding row. However, as the effect of this tube arrangement is in general comparatively small, then the above phenomenon plays no essential role especially since an increase in S_2/d produces no concrete results.

The investigations of heat transfer in tube bundles confirm well the effect of turbulization of the incoming flow on the transfer process.

It follows from the results in Fig. 13, confirmed by numerous studies, that the noticeable effect of deceleration of transfer processes in gaseous suspension due to the squeezed motion of particles may be expected only at $\gamma_v = 2 \cdot 10^{-1}$.

It is however obvious that this important conclusion does not answer whether the increase in the squeezed motion of particles leads to a change in the heat transfer equation. For a fixed tube bundle (curves in Fig. 13) this equation satisfies a laminar boundary layer condition. In order to answer this important question it is necessary to consider all the distinctive features of hydrodynamics and high intensity transfer processes from a gas to fixed particles and to particles in gaseous suspension.

One of such important peculiarities is the hydrodynamic and thermal* unsteadiness of interaction between gas and solid particles† and surfaces.

2. UNSTEADINESS OF TRANSFER PROCESSES

A solid particle (0·8 mm in size) is introduced with a velocity of $\sim$ 1 m/s (in the flow direction) into a gas stream flowing upwards with a velocity of 30 m/s; the terminal falling velocity of this particle is $v_b \simeq 4$ m/s. Under the action of the flow the velocity of the particle will increase up to its equilibrium value (26 m/s), [4], Part II. During some period of the time the regime of motion of particles will be unsteady, and the relative velocity of the particle will not be equal to its terminal falling velocity; it will be greater than v_B. Re will also vary considerably (from 350 to 50), and in the case of heat and mass transfer the transfer rate and, consequently, the Nu number will vary.

* Concentration in case of mass transfer.
† Also liquid particles.

This change in Re may lead to a change in the flow regime.

The boundary layer at the beginning of flow may be turbulent and at the end, after stabilization, laminar. The unsteadiness of the process is also aggravated by the fact that the formation of a velocity field occurs in time.

On the other hand, thermal unsteadiness of a process may also occur. As an example consider the following case: a cold gas flow of high velocity suddenly passes over a fixed heated particle surrounded by a hot gas. At the first instant there appears on the particle surface a large temperature gradient, and the heat transfer rate in a gas will be very high; as the formation of a temperature field in the gas proceeds, the rate of the process becomes stabilized.

When considering the dynamics of cooling of metallic spheres and cubes (Fig. 4, Part II) we have mentioned that in this case the existence of an unsteady period with high transfer rate was not revealed in our experiments.

In 1943 the present author and B. A. Osipov made experiments at the Tbilisi Institute of Railway Transport Engineers on combustion of carbon particles in gaseous suspension flow under the unsteady conditions when these particles were injected into the hot blast flow (at the inlet of a cyclone furnace) with a velocity of 20–100 m/s. On testing it has been established that usually about 60–85 per cent of the whole amount of fuel burnt in a very short straight section where the unsteady transfer process took place; the remaining amount of fuel was burnt in stabilized flow for approximately a time which was one order of magnitude greater than that under unsteady conditions, even using the "cyclone effect". This effect was observed many times.

The effect of unsteady heat transfer due to the formation of a temperature field will be more pronounced and be found more easily the higher the heat capacity of the ambient medium and the finer the particle size, with which there occurs interaction of flow. The relative thickness of the boundary layer increases with a decrease in Re and the unsteadiness plays here an essential role.

For coarse particles it is very difficult to study heat transfer at small Re due to natural convection. Investigations are facilitated with fine particles.

L. S. Slobodkin [19] has studied the heat transfer rate in field-bed drying of grain (d_{eq} = 3·5 mm) by a gas flow. The results of two experiments are shown in Fig. 14 at velocities of 1·5 and 3·8 m/s.

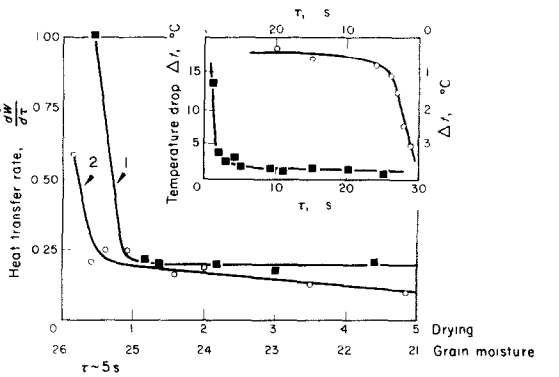

FIG. 14. Change in rate of heat transfer (drying) of grains in gas flow (at gas flow velocities: 1–3·8 m/s and 2–1·5 m/s, $d_{eq} \approx 3{\cdot}5$ mm).

The ordinate is the heat transfer rate and the abscissa is the moisture content of the grain which is a function of time from the start of passing the hot gas (t = 110°C) through the bed.

As is seen from Fig. 14, the first period of heat transfer between the gas and the grain during the first few seconds (~4 s) is characterized by a high transfer rate and it exceeds several times the heat transfer rate under steady conditions. In Fig. 8 are presented experimental points for Nu (at Re between 200 and 600) both for the constant rate of drying and for the period around 1 s when the unsteadiness of a process is greatly pronounced.

The transfer rate at the first measured point during the initial period of a process was approximately 4 times higher than that in a

steady process. After 4–5 s the heat transfer became completely stabilized, and at $Re = 200$ and 400 the Nu numbers satisfy the heat transfer for a sphere with a laminar boundary layer, equation (7), Part II. At $Re \sim 600$ the rate obtained when drying grain (with respect to Nu) is somewhat higher than the curve in equation (7), Part II.

The values of Nu obtained at the first point ($\tau \sim 1$ s) during an unsteady process greatly differ from those obtained from the curve in equation (7), Part II. Taking into account the fact that with formation of boundary (hydrodynamic, thermal and concentration) fields when the incoming turbulent flow directly interacts with a surface, the transfer rate will greatly depend upon its characteristics and, in particular, upon the "degree" of its turbulence. The character of the dependence of Re upon Nu in an unsteady process cannot satisfy the condition of a laminar boundary layer, that illustrates the location of the appropriate points in Fig. 8, Part II.

3. TURBULENCE OF INCOMING FLOW

We have already mentioned the action of turbulence of an incoming gas flowing past a sphere, cylinder and other bodies upon heat and mass transfer processes between these bodies and the gas.

If, when studying heat transfer between a gas and a sphere, the length of the stabilization section is changed, then even under the conditions of a laminar boundary layer the coefficient in equation (7) varies.

This change in the coefficient and in the value of Nu may be 25–50 per cent and more. The transfer process is intensified here due to a decrease in the thickness of a laminar boundary layer owing to an increase in the flow turbulence.

The analogous effect is obtained by increasing the degree of the flow turbulence in a tube when the transfer rate in a turbulent regime [20] is increased due to a "decrease" of the laminar sublayer*. However, the considerable stability of laminar motion near a frontal surface of a sphere, cylinder and other bodies as well as limited "resources" of such an effect essentially limits the extent of this effect upon heat transfer to the laminar boundary layer.

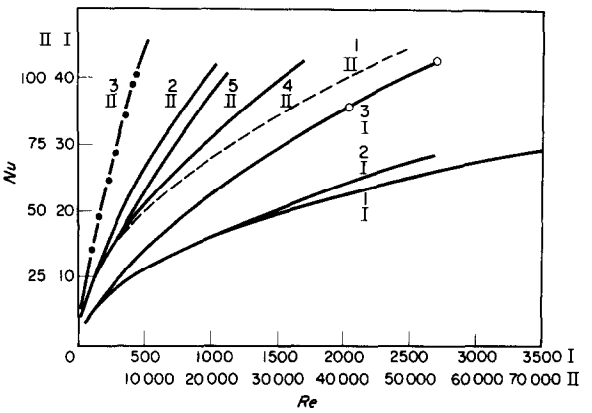

FIG. 15. Heat transfer between gas and cylinder
1—$Nu = 0{\cdot}5\,.\,Re^{0{\cdot}5}$;
2—$Nu = 0{\cdot}36\,.\,Re^{0{\cdot}5} + 0{\cdot}016\,.\,Re^{0{\cdot}82}$;
3—$Nu = 0{\cdot}36\,.\,Re^{0{\cdot}5} + 0{\cdot}039\,.\,Re^{0{\cdot}82}$;
4—$Nu = 0{\cdot}174\,.\,Re^{0{\cdot}618}$;
5—$Nu = 0{\cdot}15\,.\,Re^{0{\cdot}5} + 0{\cdot}022\,.\,Re^{0{\cdot}82}$.

There are many experimental investigations on heat transfer between a gas and a cylinder. In Fig. 15 are presented the results of some work on heat transfer between a gas and a cylinder [21], including results with different degree of turbulence of the incoming flow. At the normal degree of turbulence (up to $Re = 5000$–7000) the laminar boundary layer covers the whole surface and heat transfer obeys equation (16); at Re from 6000 to 10000 the turbulent boundary layer is formed at the rear part of a cylinder, and heat transfer is described (curve 4) by the two-term equation

$$Nu = 0{\cdot}36\,.\,Re^{0{\cdot}5} + 0{\cdot}007\,.\,Re^{0{\cdot}82}. \quad (25)$$

at $Re > 10^5$ the entire boundary layer becomes turbulent and transfer satisfies the equation

$$Nu = A\,.\,Re^{0{\cdot}82}$$

The increase in turbulence of the incoming flow leads to the intensification of the heat

* It is correct to say a "pseudolaminar" sublayer.

transfer process, with the first term of the equation at $Re < 10000$ remaining practically equal to $0{\cdot}36 \cdot Re^{0{\cdot}5}$ [see equation (17)] since the laminar boundary is covering the upstream facing surface of the cylinder.

Under these conditions the transfer process is mainly intensified due to the increase in transfer at the downstream facing surface of a cylinder in a turbulent boundary layer.

The coefficient in the second term of equation (25) increases with turbulence, achieving 0·039 in a strongly turbulent regime. It is typical that even under these conditions no noticeable decrease in a laminar boundary layer occurs at the upstream facing surface of the cylinder, and the intensification of the heat transfer process is not observed. The experimental points lie on a curve given by the equation

$$Nu = 0{\cdot}36 \cdot Re^{0{\cdot}5} + 0{\cdot}039 \cdot Re^{0{\cdot}82}. \quad (26)$$

There are fewer experimental data on heat transfer with a sphere than there are on heat transfer with cylindrical tubes and these are more contradictory. In Fig. 16 are presented the results on heat transfer with a sphere and particles of other configurations. Curve 1 satisfies equation (8), Part II, for a laminar boundary layer and curve 2 satisfies equation (20) for a turbulent boundary layer under heat transfer in gaseous suspension [17].

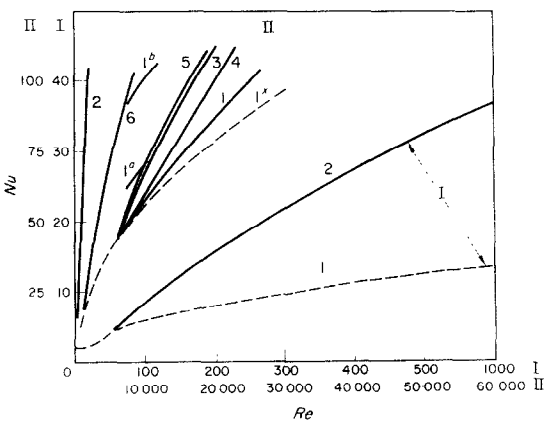

FIG. 16. Heat transfer between gas and sphere
1—sphere
1b—sphere in strongly turbulized flow
1*—$Nu = 0{\cdot}55 \cdot Re^{0{\cdot}5}$
2—$Nu = 0{\cdot}2 \cdot Re^{0{\cdot}82}$
3—rotating sphere
4—sphere with rings
5—cube
6—$Nu = 0{\cdot}06 \cdot Re^{0{\cdot}82}$ (sphere with artificially turbulized boundary layer).

Curve 1a corresponds to heat transfer with a laminar boundary layer decreased due to the increased turbulence of the incoming flow.

Curve 6 is plotted for artificial turbulization of a boundary layer at $Re = 1000$. In Fig. 8 (Part II) are given the relationships $Nu = f(Re)$ for artificial turbulization at different Re. The earlier (with respect to Re) the stable turbulization of a boundary layer is ensured, the greater is the proportionality coefficient at Re.

4. SHAPE AND ROUGHNESS OF PARTICLES

According to the data in Fig. 5 the rate of heat transfer for particles of different configuration at $Re > 10^4$ is approximately the same.

With heat transfer to bodies of poor aerodynamic shape, for example, cube, the turbulent boundary layer occurs somewhat earlier behind the flow separation region and it slightly influences the rate of the process.

Our investigations [7] on heat transfer with random and "organized" roughness of fixed spheres not only have shown the relatively small influence of roughness of spheres but also have confirmed the turbulizing effect of Prandtl's rings and special grooves upon a boundary layer on a cylindrical tube with "flaps" (A. A. Gukhman's data).

Prandtl's rings on a sphere as well as tube flaps lead to artificial turbulization of a boundary layer at a definite place at the surface of a tube and a sphere. This allows, with sufficient accuracy, for heat transfer equations to be written which take into account the part of a surface occupied by laminar and turbulent boundary layers. In Fig. 15 is presented curve 5 well describing Gukhman's experiments and plotted according to a two-term equation

$$Nu = 0{\cdot}15 \cdot Re^{0{\cdot}5} + 0{\cdot}22 \cdot Re^{0{\cdot}82} \quad (27)$$

where the coefficient equal to 0·15 at $Re^{0.5}$ is determined by the angle of setting the flaps.

Some valuable results on the effect of roughness and other ways of artificial turbulization of a boundary layer as well as on the effect of roughness upon the rate of heat transfer in a turbulent regime were obtained by V. M. Buznik [25].

As the investigations [7] have shown, the effect of roughness of a fixed sphere becomes pronounced at sufficiently high values of Re ($\sim 10^4$) and at Re up to 10^3 the roughness does not essentially influence the rate of heat and mass transfer in gaseous suspension.

5. ROTATION OF PARTICLES

One of the peculiarities of motion and interaction between particles and gas in gaseous suspension is the rotation of solid particles in a gas flow and thus, the change in the direction of their motion.

The rotation of fine solid particles (up to 300–600 μ) inevitably appears in gaseous suspension even for spherical particles, without speaking about irregular shape particles. Collisions, velocity gradients normal to the flow of gaseous suspension, turbine pulsations, transverse displacements of particles, irregular shape of particles, etc. promote the onset and increase of rotation of particles. As investigations [3] show the velocity of rotation of particles in gaseous suspension may be very high, and the number of revolutions may achieve several thousands per min.

What does the rotation of particles in gaseous suspension contribute to heat and mass transfer? To answer this question, first of all, consider heat transfer with a rotating fixed cylinder, for which due to constant velocities along the surface* the process appears to be more simple than in the case of a rotating fixed sphere.

For the first time a thorough experimental study of heat transfer with a rotating cylinder was made by A. M. Mikheev ([14], Part II) who established that the curve $Nu = f(Re)$ is similar to that for ordinary flow past a non-rotating cylinder but an essential intensification of heat transfer due to rotation was observed.

The results of previous investigations [27–29] have confirmed the data obtained by M. A. Mikheev and allowed for quantitative estimation of the intensification effect due to the additional motion of a gas at a surface caused by the tube rotation. Assuming, according to [20],

$$Re_f \approx \sqrt{(Re^2 + Re_{rot}^2)} \tag{28}$$

it is possible to correlate the data with and without the rotation of a cylinder by a single curve $Nu = f(Re)$

$$Nu \approx 0{\cdot}36 \,.\, Re^{0.5} + 0{\cdot}008 \,.\, Re^{0.82} \tag{29}$$

The experimental data [20] lie satisfactorily on the curve satisfying this equation. Some scatter of the experimental points obtained by various authors may be explained by the different degree of turbulence of the incoming flow.

In this case it is important that the rotation of the cylinder changes only the actual flow velocity but does not lead to an earlier onset of turbulence of the boundary layer. Vibrations and oscillations affect the transfer at a cylinder in the same way.

The influence of rotation* of a sphere in flow upon the boundary layer differs qualitatively from that of a cylinder. Since the velocities at different points of the sphere surface are different, there occurs formation of complex and very peculiar velocity profiles and of a moving line of boundary layer separation. The flow past a downstream facing surface changes and a vortex "street" is formed.

All this is amplified by the fact that the orientation of the axis of rotation of particles in gaseous suspension may vary in space causing

* The rotation axis is normal to the gas flow.

* When the rotation axes do not coincide with the direction of the incoming flow.

artificial hydrodynamic unsteadiness of a process. Under certain conditions the complex effect of rotation of particles upon the boundary layer should inevitably lead to the disturbance of the frontal part of the boundary layer and the expansion of the part of the surface covered by the turbulent boundary layer which appeared at the rear part of the body.

The investigations of the effect of rotation of fixed spherical particles upon the rate of heat transfer [7] have confirmed the intensifying action of rotation but have not revealed this effect upon the boundary layer in the region of its proposed turbulization.

Z. P. Gorbis [3], analyzing these data with particular reference to any change due to rotation of spheres, has concluded that a turbulent boundary layer is formed over the whole surface of particles. The deduction of the fact that the rotation of the sphere turbilizes the boundary layer was based [3] on the fact that in a dimensionless heat transfer equation Z. P. Gorbis has obtained the exponent on Re approximately equal to 0·8.

The results obtained are simple and uniquely confirm our conclusion [4] on the mechanism of heat transfer intensification in gaseous suspension and seem to settle the question. Unfortunately, the precise treatment of experimental data disturbed the simplicity and uniqueness of this conclusion.

In Fig. 17 are presented the data [7] on rotating spheres with particular reference to the additivity of the effect of flow and rotation upon the value of Re_{eq} which is determined from equation (28). As is seen from Fig. 17 the influence of rotation is indicated mainly in the additional relative motion of particles, and the contribution of turbulization to the boundary layer at the rear part of a sphere for $Re_{eq} > 0{\cdot}5\text{–}1{\cdot}0 \cdot 10^4$ is only observed to little extent.

There occurs no total turbulization of the boundary layer due to rotation of fixed spheres in the region up to 600 rpm. The reason for this probably lies in the high stability of the frontal part of a laminar boundary layer.

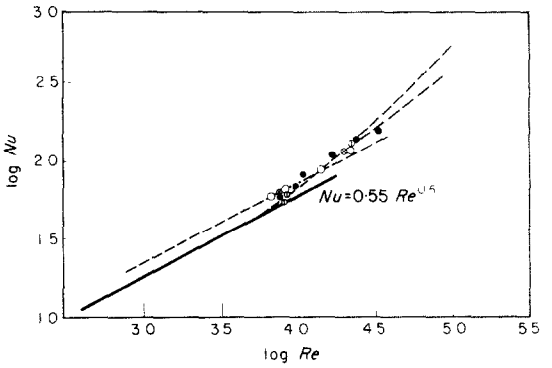

FIG. 17. Effect of Re_{eff} upon rate of heat transfer between gas and rotating sphere (Experimental points at different speeds of sphere rotation).

Thus, the rotation of particles does not cause artificial turbulization of a laminar boundary layer under the developed flow conditions but it promotes persistence of the available or appearing turbulent boundary layer and even expansion of its boundaries along the surface of a stream-lined body or particle.

As we have already mentioned, under usual conditions the turbulent boundary layer, even at the rear part of a sphere, is formed as a rule with an increase in Re_{eq} above 3000–10000. The rotation of a sphere therefore intensifies a process only at Re_{eq} exceeding several thousands but this of course little intensifies transfer processes in gaseous suspension.

For the rotation of particles to considerably influence the intensification of transfer, it is necessary to have other additional sources for the creation of artificial turbulization of the boundary layer which will ensure its onset at considerably lower values of Re.

As is obvious from our analysis, that such main sources for gaseous suspension are hydrodynamic unsteadiness and turbulence of total (incoming) flow. When there is no laminar layer or it has been destroyed, then under certain conditions the rotation as well as oscillation of particles may maintain and develop turbulence and unsteadiness of processes of interaction between the particles and the gas flow.

6. TRANSFER PROCESSES IN GASEOUS SUSPENSION

As is clearly seen from our analysis, the transfer processes in gaseous suspension are greatly complicated by simultaneous interaction of different factors such as hydraulic and thermal unsteadiness, external turbulence, mutual interaction and collision of particles, their "roughness" and rotation. Each of these factors separately sometimes makes a considerable and sometimes negligible contribution but it is very important to emphasize that in most cases it is their combination which intensifies transfer between particles and a gas in gaseous suspension.

The mechanism of heat and mass transfer in gaseous suspensions with fine particles at Re_{eq} up to 5–10 is a simple one. In this case over a wide range of γ_v the values of Nu will be close to 1·5–2·0* and the transfer processes may be calculated with sufficient accuracy if a high rate of mixing of gas and solid particles is ensured. Strictly speaking, the production and maintenance of homogeneous gaseous suspension in the active volume of an apparatus has to be secured.

It is not very simple to provide "homogenization" of gaseous suspension in the active volume since the time of heating of fine particles is 10^{-5}–10^{-2} s and, consequently, the active volume of the apparatus is not large. For homogeneous gaseous suspension at $Bi < 0{\cdot}1$–$0{\cdot}2$ the time of heating is determined by equation (22) if heat dissipation along the flow is relatively small.

If molecular transfer along the flow at large temperature (concentration) gradients in this direction ($\gamma_v > 0{\cdot}1$) may not be neglected, then the calculation should take into account a change in Nu determined by integrating equation (30) with inclusion of molecular transfer and an appropriate change in Nu_{lim} over a range of 1·5–10·0. With heat dissipation (due to molecular transfer) along the flow Nu_{eff} may be considerably less than 2 ([1], Part II).

* Depending on the shape of particles.

For the case of dissipation of heat and mass transfer due to molecular diffusion and heat conductivity along the flow, $N\dot{u}_{eff}$ may be determined by the following equation obtained by integrating the differential equation

$$N^L = Pe.\tfrac{1}{8}[\sqrt{(Pe^2 - B\,.\,Nu_{lim})} - Pe]$$

$$-\Delta = \bar{w}_z \frac{d\bar{c}}{dz} - D\frac{d^2c}{dz^2}. \qquad (30)$$

In equation (30) the value of Nu_{lim} varies from 1·5–2·0 to 10 at high γ_v close to 0·5 [1] and at $B^\circ \approx 15$–16.

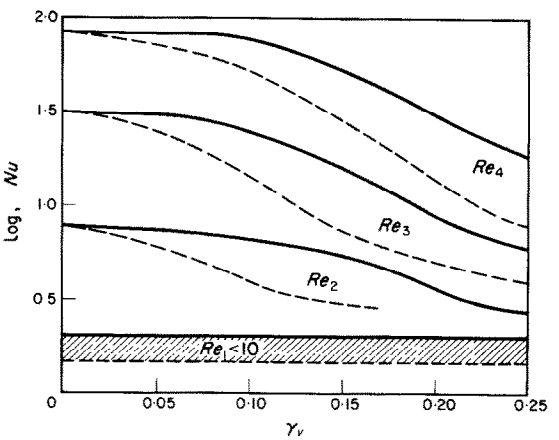

FIG. 18. Effect of gaseous suspension concentration upon rate of heat and mass transfer from gas to particles (at different values of Re: $Re_1 < Re_2 < Re_3 < Re_4$).

The dependence of the number Nu upon concentration of gaseous suspension is presented in Fig. 18. At $Re_{eff} > 10$ this dependence (without regard for heat dissipation and a change in Nu_{lim}) is presented as a straight line parallel to the abscissa axis, which corresponds to $Nu = \text{const.}$ ($\gamma_v < 0{\cdot}2$).

The increase in Re_{eff} should inevitably lead to the intensification of transfer at any γ_v and, consequently, the straight line satisfying $Re < 10$ in Fig. 18 represents a limiting case. Under normal conditions the values of Nu will always be higher than the appropriate lower limiting ones.

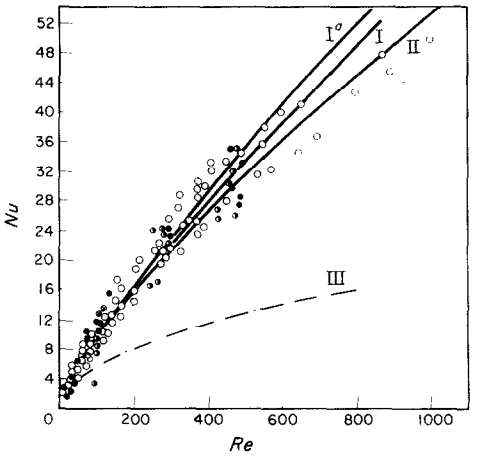

FIG. 19. Heat transfer between gas and solid particles in gaseous suspension

I $Nu = 0{\cdot}2 \cdot Re^{0{\cdot}82}$
Ia — $Nu = 0{\cdot}2 \cdot Re^{0{\cdot}83}$
II — $Nu = 0{\cdot}15 \cdot R^{e0{\cdot}83} + 0{\cdot}26 \cdot Re^{0{\cdot}5}$
III — $Nu = 0{\cdot}56 \cdot Re^{0{\cdot}5}$.

The increase in Re_{eff} due to increase in relative velocity or size of particles as well as due to their oscillation or rotation at small γ_v leads to an increase in Nu in accordance with the appropriate relation determined by the characteristics of the boundary layer. In Fig. 18 this increase in Nu is qualitatively shown for different values of Re_{eff} at γ_v close to zero.

The method of calculation of transfer processes in gaseous suspensions may be based on equation (20) for a sufficiently wide range of conditions: for Re_{eff} up to 400–600, for γ_v at small values of Re_{eff} without restrictions* and for large values of Re_{eff} up to γ_v of the order of 10^{-2}.

In equation (22) the values of α are determined from the appropriate dimensionless dependences of heat transfer $[Nu = f(Re)]$ which are for ordinary conditions graphically presented in Fig. 19 [2].

The rate of heat transfer for fine particles in gaseous suspensions is very high even at $Nu = 2$ and it may be greatly intensified by increasing Re_{eff} and by developing still earlier turbulization of the boundary layer and thus, consequently, increasing the coefficient at $Re^{0{\cdot}82}$ in the heat transfer equation.

If the contribution of unsteadiness may be mainly achieved by the conditions of gaseous suspension formation, then the increase in the value of Re_{eff} may be attained by using centrifugal forces in a curvilinear flow, different oscillations and motion regimes.

The application of homogeneous gaseous suspension in a heat exchanger and in reactors of different types undoubtedly has good prospects since they may operate, with intense high-temperature processes. The time of heating and cooling (reaction) of gas (particles) in gaseous suspension may be down to one tenthousandth and one hundredthousandth of a second.

* With regard for variations in Nu_{lim} due to longitudinal "molecular" heat dissipation.

REFERENCES

17. I. M. FEDOROV, *Theory and Prediction of Drying in Suspended State*. Gosenergoizdat, Moscow (1955).
18. V. M. ANTUF'EV and L. S. KAZACHENKO, *Heat Transfer and Resistance of Convective Heating Surfaces*. ONTI HKTP SSSR, Leningrad–Moscow (1938).
19. L. S. SLOBODKIN, Heat and mass transfer between gas and single grains, *Inzh. Fiz. Zh.* **10**, 26–31 (1962).
20. V. M. BUZNIK, *Heat Transfer in Ship Power Plants*. Izd. "Sudostroyeniye", Leningrad (1967).
21. Z. F. CHUKHANOV, Intensification of convective heat transfer by artificial turbulization of a boundary layer, *DAN SSSR* **57** (1), 35–38 (1947).
22. L. S. EIGENSON, On a drag of circular cylinder in transverse flow, Preprints of the Conference on Simulation of Thermal Devices, *Izd. AN SSSR*, Moscow (1938).
23. A. A. GUKHMAN, *Physical Fundamentals of Heat Transfer*. Izd. "Gosenergoizdat", Moscow (1934).
24. L. F. KOZLOV, On calculation of transition of a laminar boundary layer into a turbulent one under the action of incoming flow, *Inzh. Fiz. Zh.* **3**, 103–106 (1962).
25. B. M. BUZNIK, G. A. ARTEMOV, B. N. BANDURA and A. M. FEDOROVSKY, Study of effect of profile roughness of wing elements on heat transfer rate, *Inzh. Fiz. Zh.* **14**, 460–469 (1968).
26. T. R. GALLOWAY and B. H. SAGE, Thermal and material transfer from spheres. Prediction of local transport, *Int. J. Heat Mass Transfer* **11**, 523–537 (1968).
27. G. A. STEWARD, Free-convection heat transfer from a rotating horizontal cylinder to ambient air with interferometric study of flow, *Trans. Am. Soc. Mech. Engrs* No. 8 (1955).
28. D. DROPKIN, Natural convection heat transfer from a horizontal cylinder rotating in air, *Trans. Am. Soc. Mech. Engrs* No. 4 (1957).
29. W. KAYS, Heat transfer from a rotating cylinder with and without crossflow, *Trans. Am. Soc. Mech. Engrs* No. 1 (1958).

Abstract—Heat and mass transfer processes in gas suspension (from a gas to particles) are considered, and the main factors influencing their intensity are established in the paper.

The influence of gas suspension concentration, hydrodynamic and thermal unsteadiness, turbulization of incoming flow, rotation of particles and their shape upon transfer is analysed.

The system of calculating transfer processes in gas suspension is substantiated. It has been shown that in gas suspension of fine particles transfer processes occur with very high intensity, sharply increasing with concentration. It has been established that there may take place no transfer deceleration due to squeezed motion in gas suspension of fine particles at $Re < 10$. The ways of achieving high efficiency of heat exchangers and reactors using gas suspension are shown. The time of heating a gas (particles) in "homogeneous" gas suspension may be up to ten thousandth and hundred thousandth fractions of a second.

TRANSPORT DE CHALEUR ET DE MASSE ENTRE UN GAZ ET UN MATERIAU GRANULAIRE

Résumé—Les processus de transport de chaleur et de masse dans une suspension gazeuse (depuis un gaz jusqu'aux particules) sont considérés, et les facteurs principaux influençant leur intensité sont établis dans l'article.

L'influence de la concentration de la suspension gazeuse, de l'instationnarité hydrodynamique et thermique, de la mise en turbulence de l'écoulement d'entrée, de la rotation des particules et de leur forme sur le transport est analysé.

Le système de calcul des processus de transport dans une suspension gazeuse est établi. On a montré que les processus de transport dans une suspension gazeuse de particules fines se produisent avec une intensité très élevée, augmentant fortement avec la concentration. On a établi qu'il ne peut y avoir aucune décélération du transport due au mouvement de pression dans une suspension gazeuse de particules fines à $Re < 10$. Les moyens d'obtenir un rendement élevé d'échangeurs de chaleur et de réacteurs employant des suspensions gazeuses sont indiqués. Le temps de chauffage d'un gaz (particules) dans une suspension gazeuse "homogène" peut aller jusqu'à dix et cent millisecondes.

WÄRME- UND STOFFAUSTAUSCH ZWISCHEN GAS UND FEINKÖRNIGEM MATERIAL

Zusammenfassung—Es werden in der Arbeit die Wärme- und Stoffübergangsprozesse in Gassuspensionen (Gas-Festkörper) behandelt und die Hauptfaktoren welche ihre Intensität beeinflussen.

Der Einfluss von Konzentration der Gassuspension, hydrodynamischer und thermischer Unstetigkeit, Verwirbelung der Eintrittsströmung, der Teilchen und ihrer Form auf den Wärmeübergang wird analysiert.

Das Berechnungssystem für Übergangsprozesse in Gassuspensionen wird erhärtet. Es wird gezeigt, dass in Gassuspensionen mit feinen Teilchen die Übergangsprozesse mit grosser Intensität erfolgen und mit der Konzentration stark zunehmen. Es ergab sich, dass für $Re < 10$ in Gassuspensionen feiner Teilchen keine Übergangsverschlechterung infolge von Querschnittsverengung eintreten muss.

Möglichkeiten zur Erzielung grosser Wirkungsgrade von Wärmeübertragern und Reaktoren die Gassuspensionen enthalten, werden gezeigt. Die Aufheizzeit für ein Gas (Festteilchen) in einer "homogenen" Gassuspensionen kann bis zum zehn- oder hunderttausendsten Teil einer Sekunde betragen.