state of the heat transport surface due to precipitate formation. Beforehand deoxygenation of fuels encourages a reduction in precipitate formation and reduction in heat liberation intensity.

NOTATION

q, thermal flux density, kW/m^2; α, heat liberation coefficient, $kW/(m^2 \cdot K)$; P, pressure, MPa; C_{O_2}, volume concentration of oxygen dissolved in fuel, %.

LITERATURE CITED

1. N. M. Turchin, A. A. Tsyganok, A. A. Gribov, and G. V. Bodorenko, Inzh. Fiz. Zh., 52, No. 3, 383-386 (1987).
2. N. F. Dubovkin, V. G. Malanicheva, Yu. P. Massur, and E. P. Fedorov, Physicochemical and Utilization Properties of Reactive Fuels: A Handbook [in Russian], Moscow (1985).
3. A. M. Kutepov, L. S. Sterman, and N. G. Styushin, Hydrodynamics and Heat Exchange in Vapor Formation [in Russian], Moscow (1986).
4. Heat Exchanger Handbook, Vol. 1 [in Russian], Moscow (1987).
5. P. D. Martini and L. D. Spadachhini, Énerg. Mashin. Ustanov., No. 4, 89-96 (1986).
6. N. M. Emanuel', E. T. Denisov, and Z. K. Maizus, Liquid Phase Hydrocarbon Oxidation Chain Reactions [in Russian], Moscow (1965).

COMPUTATION OF THE RADIATION FLUX EMANATING FROM A HIGHLY DISPERSE LAYER

V. V. Levdanskii and V. G. Leitsina

UDC 536.3

Problems of the radiation of a highly disperse layer and of radiation transfer in a disperse layer-enclosing surface system are examined. The influence is analyzed of nonisothermy on the radiation flux density emanating from the layer. A dependence of this quantity on the system parameters is found.

The necessity for the solution of problems associated with radiation energy transfer in highly disperse media (porous bodies, aerodispersed systems) occurs in the description of many technological processes. In a number of cases the disperse system with moving particles that is under consideration is enclosed in a certain volume such that heat transfer by radiation occurs between it and the enclosing surfaces [1]. If the surface temperature is below the particle temperature, a temperature drop can occur in the disperse medium [2]. The problem of a radiator in which energy releases are realized by atomization of hot fluid drops in cosmic space and cooling them by radiation heat extraction and then collection of the cold particles is examined in [3]. All the problems mentioned are associated with a computation of the heat transfer by radiation from a disperse medium with enclosing surfaces or of heat elimination into outer space.

A survey of the different models utilized to compute heat transfer by radiation in disperse systems in both the case of a fixed skeleton of a porous body and for moving particles of condensed phase (in particular, for fluidized media) is presented in [2, 4, 5]. We shall later use the random walk model of particles (photons in this case) in a macroparticle medium that can be their sources or sinks. According to this model, the disperse medium is simulated by a homoeneous system of chaotically distributed fixed opaque spherical particles of radius r. Such a model is applied in [6] to compute the mass transfer in a subliming porous layer for a free-molecule gas flow. Taking account of the known analogy between mass transfer processes for a free-molecule gas flow and radiation transfer [7], this approach was utilized in [5] to compute radiation propagation in a porous layer. The

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.

Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 59, No. 4, pp. 586-593, October, 1990. Original article submitted August 4, 1989.

0022-0841/90/5904-1266$12.50

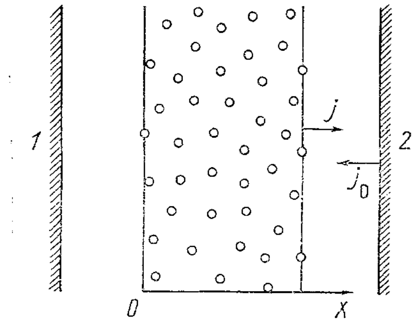

Fig. 1. Geometric diagram of the problem.

model mentioned describes real highly disperse media sufficiently adequately, i.e., highly porous bodies of globular structure and aerodisperse systems.

The problem of heat transfer by radiation from a plane-parallel disperse layer with enclosing surfaces (Fig. 1) is solved in this paper by using this model. The case of a plane-parallel layer (i.e., the one-dimensional problem) is examined for simplicity and clearness of the computations as well as in connection with the possibility of comparing the results obtained with data existing in the literature that refer also to plane-parallel layers in the majority of cases. Let us note that these results can be utilized even for radiating layers bounded by curved surfaces in the case when the layer thickness is much less than the radii of curvature of the surfaces.

Utilization of the analogy between the free-molecule gas flow process in porous bodies and the heat transfer process by radiation is justified if and only if wave effects can be neglected, i.e., for a radiation wavelength much less than the diameter of the spheres simulating the particles of the disperse system and the spacings between them. As is noted in [2], these conditions are satisfied for high-temperature fluidized systems and, moreover, the approximation of gray radiation particles can be used. Further computations are also performed within the framework of the mentioned assumptions, where the medium between the particles is here assumed transparent.

Let us assume that isotropic scattering of the radiation by the particles occurs while the surface emissivity (radiativity) equals its absorptivity. In this case the integral equation for the radiation power density emitted by unit volume of a disperse layer of thickness L has the following form for taking account of the intrinsic thermal radiation of the spheres [5]

$$\overline{\Phi}(x) = l(1-\varepsilon)\Big[\int_0^1 \overline{\Phi}(\xi)\exp\{-2l|x-\xi|\}\,d\xi + 2\Pi j_0(\exp\{-2lx\} + \exp\{-2l(1-x)\})\Big] + 4\Pi\varepsilon l\overline{T}^4(x). \quad (1)$$

The first components in the square brackets in (1) describes the radiation incident in unit volume of the disperse layer in the neighborhood of the point x from the rest of the volume, the other two are from the outer surfaces 1 and 2. Here the dimensionless quantities

$$x = \frac{X}{L},\ j_0 = \frac{J_0}{\sigma T_c^4},\ \overline{\Phi} = \frac{\Phi L}{\sigma T_c^4},\ l = \frac{L}{\lambda},\ \overline{T} = \frac{T}{T_c},$$

are introduced, where J_0 is the diffuse radiation flux density incident on each of the layer boundaries; Φ and T are the dimensional radiation power density and the temperature of the porous layer, $T_c = T(L/2)$, λ is the photon mean free path determined by analogy with the molecule mean free path with respect to fixed spheres [8]

$$\lambda = \frac{4\Pi}{3(1-\Pi)}\,r.$$

Let us note that in (1) as in [5, 6] also, the replacement of the exponential integral functions by exponentials is used, as is often applied in the solution of radiation transfer problems [9]

The radiation flux density j_0 in (1) equals the sum of two components describing the intrinsic thermal radiation of the outer surface and the radiation of the disperse surface reflected by it, respectively:

$$j_0 = \varepsilon_0 \overline{T}_0^4 + (1-\varepsilon_0) j. \tag{2}$$

The flux density j contains radiation emanating from the volume of the disperse layer, the radiation j_0 from the outer surface 2 reflected by the layer outer boundary, and the radiation j_0 from the surface 1 transmitted through the layer as well as the intrinsic thermal radiation of this outer boundary

$$j = \frac{1}{2}\int_0^1 \overline{\Phi}(\xi)\exp\{-2l(1-x)\}\,d\xi + [(1-\Pi)(1-\varepsilon) + \Pi\exp\{-2l\}]\,j_0 + (1-\Pi)\,\varepsilon\overline{T}^4(1). \tag{3}$$

It follows from (2) and (3)

$$j_0 = \gamma\left[\varepsilon_0\overline{T}_0^4 + (1-\varepsilon_0)(1-\Pi)\,\varepsilon\overline{T}^4(1) + \frac{1-\varepsilon_0}{2}\int_0^1 \overline{\Phi}(\xi)\exp\{-2l(1-\xi)\}\,d\xi\right], \tag{4}$$

where $\gamma = \{1-(1-\varepsilon_0)[(1-\Pi)(1-\varepsilon) + \Pi\exp\{-2l\}]\}^{-1}$.

We represent the temperature distribution in the layer that satisfies the symmetry condition in the form

$$T^4(x)/T_c^4 = 1 + 2\alpha\left[1 - \mathrm{ch}\left\{\beta\left(x - \frac{1}{2}\right)\right\}\right]. \tag{5}$$

For appropriate values of the coefficients α and β such a dependence adequately approximates the real temperature profile with an abrupt drop in the temperature to the layer boundaries. Moreover, utilization of (5) and the mentioned replacement of the exponential integral functions by exponentials permits finding an approximate analytic solution of (1) by the method described in [5, 6].

Differentiating (1) twice with (5) taken into account and combining the result with (1), we obtain the differential equation

$$\frac{d^2\overline{\Phi}}{dx^2} - 4\varepsilon l^2\overline{\Phi} = 8\Pi\varepsilon l\alpha(4l^2-\beta^2)\,\mathrm{ch}\left\{\beta\left(x-\frac{1}{2}\right)\right\} - 16\Pi\varepsilon l^3(1+2\alpha),$$

whose solution has the form

$$\overline{\Phi} = a_1\exp\{2\sqrt{\varepsilon}\,lx\} + a_2\exp\{-2\sqrt{\varepsilon}\,lx\} + \frac{8\Pi\varepsilon l\alpha(4l^2-\beta^2)}{\beta^2-4\varepsilon l^2}\,\mathrm{ch}\left\{\beta\left(x-\frac{1}{2}\right)\right\} + 4\Pi l(1+2\alpha). \tag{6}$$

Substituting (4)-(6) into (1) and equating coefficients of exp{−2ℓx} and exp{2ℓx}, we obtain a system of linear algebraic equations to determine the coefficients a_1 and a_2 (for $\varepsilon \neq 1$):

$$\begin{aligned}
&\frac{1}{1+\sqrt{\varepsilon}}\,[\Pi\gamma(1-\varepsilon_0)(\exp\{2\sqrt{\varepsilon}\,l\} - \exp\{-2l\}) - 1]\,a_1 + \\
&+ \frac{1}{1-\sqrt{\varepsilon}}\,[\Pi\gamma(1-\varepsilon_0)(\exp\{-2\sqrt{\varepsilon}\,l\} - \exp\{-2l\}) - 1]\,a_2 = \\
&= 4\Pi l\left\{1+2\alpha - \gamma\left[\Pi(1-\varepsilon_0)(1+2\alpha)(1-\exp\{-2l\}) + \right.\right. \\
&\left.\left. + (1-\varepsilon_0)(1-\Pi)\,\varepsilon\left(1+2\alpha-2\alpha\,\mathrm{ch}\frac{\beta}{2}\right) + \varepsilon_0\overline{T}_0^4\right]\right\} + \\
&+ \frac{8\Pi\varepsilon l^2\alpha(4l^2-\beta^2)}{\beta^2-\varepsilon l^2}\left\{\frac{\exp\left\{\frac{\beta}{2}\right\}}{2l-\beta} + \frac{\exp\left\{-\frac{\beta}{2}\right\}}{2l+\beta} + \right. \\
&+ \Pi\gamma(1-\varepsilon_0)\left[\frac{1}{2l-\beta}\left(\exp\left\{\frac{\beta}{2}-2l\right\} - \exp\left\{-\frac{\beta}{2}\right\}\right) + \right.
\end{aligned} \tag{7}$$

$$+\frac{1}{2l+\beta}\left(\exp\left\{-\frac{\beta}{2}-2l\right\}-\exp\left\{\frac{\beta}{2}\right\}\right)\Bigg]\Bigg\},$$

$$\left(\frac{1}{1+\sqrt{\varepsilon}}-\frac{\exp\{2\sqrt{\varepsilon}\,l\}}{1-\sqrt{\varepsilon}}\right)a_1+\left(\frac{1}{1-\sqrt{\varepsilon}}-\frac{\exp\{-2\sqrt{\varepsilon}\,l\}}{1+\sqrt{\varepsilon}}\right)a_2=0. \tag{7}$$

The second equation of the system (7) is simplified with the first taken into account.

Using the values of a_1 and a_2 found from (7), we determine the radiation flux densities j_0 and j and the resultant radiation flux density

$$j_r=j-j_0=\varepsilon_0(j-\overline{T}_0^4), \tag{8}$$

according to (2), (3) and (6).

For ε = 1 the skeleton absorbs all the radiation incident on it and $\overline{\Phi}$ is determined by the intrinsic thermal radiation of the sphere surfaces. It follows form (1) that in this case

$$\overline{\Phi}(x)=4\Pi l\overline{T}^4(x). \tag{9}$$

The disperse layer can be characterized by the dimensionless density of the radiation flux j emanating from it which plays the part of a certain effective layer emissivity. However, in the isothermal case (α = 0) the effective emissivity can also be introduce by another manner. The results of computations using (3), (6)-(8) for α = 0 indicates that the resultant radiation flux density can be represented by analogy to the problem of two radiating surfaces [10] in the form

$$j_r=\frac{1}{\dfrac{1}{\varepsilon_0}+\dfrac{1}{\varepsilon_{\text{eff}}}-1}(1-\overline{T}_0^4), \tag{10}$$

where ε_{eff} is the effective emissivity of the disperse layer determined by its porosity and the emissivity of the skeleton and independently of the external surface characteristics. This means that the disperse layer is equivalent in this case to a surface with emissivity ε_{eff}. For ε_0 = 1 (the outer surfaces are absolutely black) we have according to (10)

$$j_r=\varepsilon_{\text{eff}}(1-\overline{T}_0^4).$$

The system (7) is simplified for a thick layer ($\ell \gg 1$) when according to the second equation

$$a_2=a_1\exp\{2\sqrt{\varepsilon}\,l\}. \tag{11}$$

Since in conformity with the above the ε_{eff} is independent of ε_0, we set ε_0 = 1 in the first equation in (7) for simplicity, which results in the isothermal case in the expression

$$a_2=4\Pi l(\sqrt{\varepsilon}-1)(1-\overline{T}_0^4). \tag{12}$$

Substituting (11) and (12) into (6), (3), (8) and (10) we find that for $\ell \gg 1$

$$\varepsilon_{\text{eff}}=\varepsilon'_{\text{eff}}=(1-\Pi)\varepsilon+\frac{2\Pi\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}. \tag{13}$$

Let us not that for $\varepsilon \neq 1$ $\varepsilon'_{\text{eff}} > \varepsilon$.

The effective emissivity of a fluidized bed is computed in [2, 11] by using the method of stops (a set of elementary reflecting, transmitting, and emitting layers). The formula

$$\varepsilon'_{\text{eff}}=\varepsilon^{0,4}, \tag{14}$$

is here proposed to estimate $\varepsilon'_{\text{eff}}$ in the range $0.4 < \Pi < 0.95$.

The expression (14) does not contain the porosity Π in contrast to (13). Comparison of the results of computing $\varepsilon'_{\text{eff}}$ by these formulas shows that for Π = 0.8 the agreement is best: for ε = 0.2 the difference is about 2% while it practically vanishes as ε increases. For other values of $\varepsilon'_{\text{eff}}$ the discrepancy between the quantities ε computed by means of (13) and (14) will be the more substantial, the smaller the $|\Pi - 0.8|$ and the larger the Π = 0.6, for instance, it is 15% for ε = 0.2.

For ε = 1 in the isothermal case when according to (9), $\overline{\Phi} = 4\Pi\ell$, we obtain $\varepsilon_{\text{eff}} = 1 - \Pi\exp\{-2\ell\}$, i.e., ε_{eff} = 1, from (2), (3), (8) and (10).

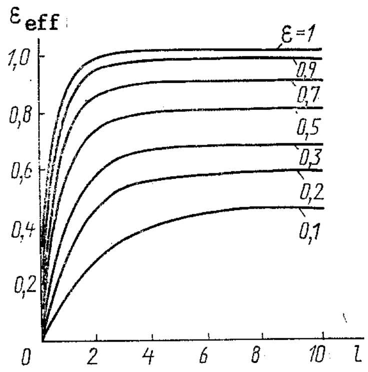

Fig. 2

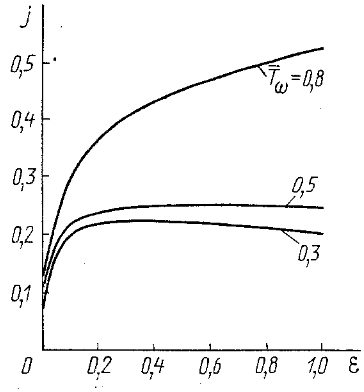

Fig. 3

Fig. 2. Dependence of the effective emissivity of an isothermal disperse layer on its thickness for Π = 0.9.

Fig. 3. Dependence of the radiation flux density emanating from a nonisothermal disperse layer on the emissivity of the skeleton surface for Π = 0.9.

In the absence of outer surfaces ($j_0 = 0$, which is equivalent to $\varepsilon_0 = 1$, $\tilde{T}_0 = 0$) the quantity ε_{eff}, according to (10), determines the radiation flux density j emanating from a layer, i.e., in this case ε_{eff} agrees with the effective quantity mentioned earlier. The dependences of ε_{eff} on the thickness of an isothermal disperse layer found from (7), (6), and (3) are represented in Fig. 2. It is seen from the figure that the greater the ε, the more rapidly (i.e., for smaller ℓ) is the asymptotic value ε'_{eff} determined by (13) achieved. The nature of the dependence $\varepsilon_{eff}(\ell)$ here agrees with the dependence presented in [10] for the effective emissivity of a cylindrical cavity on its relative depth.

According to computations, in the presence of external surfaces for $\bar{T}_0 < 1$ the values of j exceed the values of the flux density in the case of an individual layer ε_{eff}, where the smaller the ε and the ε_0, the greater the difference $j-\varepsilon_{eff}$ for a fixed $\bar{T}_0$. As regards the density of the resultant flux j_r, then it diminishes in conformity with (10).

Let us, furthermore, examine a nonisothermal disperse layer whose temperature is described by the relationship (5). We assume that an abrupt temperature change occurs near the layer boundaries, i.e., $\beta \gg 1$. Then according to (5)

$$\alpha \simeq (1-\bar{T}_w^4)\exp\left\{-\frac{\beta}{2}\right\}, \tag{15}$$

i.e., $\alpha \ll 1$ (here $\bar{T}_w = \bar{T}(0) = \bar{T}(1)$).

We obtain from (7) for $\beta \gg 1$, $\alpha \ll 1$

$$a_2 = 4\Pi l(\sqrt{\varepsilon}-1)\left[1+\frac{2\varepsilon l\alpha(2l+\beta)}{\beta^2-4\varepsilon l^2)}\right]\exp\left\{\frac{\beta}{2}\right\}. \tag{16}$$

Taking account of (11) and (16) we write the expression for the radiation flux density emanating from the layer

$$j = \varepsilon'_{eff} - \alpha\varepsilon\left[1-\Pi+\frac{4\Pi l}{(1+\sqrt{\varepsilon})(\beta+2\sqrt{\varepsilon}\,l)}\right]\exp\left\{\frac{\beta}{2}\right\}. \tag{17}$$

It follows from (17) that the function j can be both monotonic and with a maximum (see Fig. 3) for identical values of β for different α (i.e., different values of $\bar{T}_w$). The nature of the dependence j(ε) is determined by the relative difference in the temperatures at the center and at the edges of the layer $1-\bar{T}_w$: the passage to a non-monotonic function occurs as it increases. It is seen from Fig. 3 that the dependence of j on ε in the nonisothermal case is noticeably weaker than in the isothermal case when $j \to 1$ as $\varepsilon \to 1$. In contrast to the isothermal case, there is here a value of ε for which the equality $j = \varepsilon$ is satisfied, i.e., the disperse layer becomes equivalent to a continuous plane surface whose emissivity agrees with the emissivity of the skeleton surface. The kind of j(ε) curves mentioned is explained by the fact that an increase in the degree of particle emissivity of

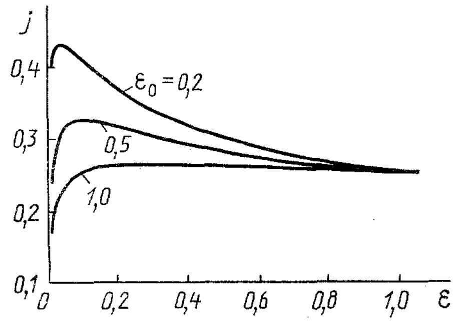

Fig. 4. Dependence of the radiation flux density emanating from a nonisothermal disperse layer in the presence of external surfaces on the emissivity of the skeleton surface for Π = 0.9, $\tilde{T}_0 = \tilde{T}_W = 0.5$.

the disperse layer will result, on one hand, to growth of the particle radiation and, on the other, to diminution of the probability of emergence of photons from the layer that had originated at its cetral (hotter) part, and an increase in the role of the photons appearing near the boundaries where the temperature is lower.

It follows from (15) and (17) that the steeper the temperature profile (i.e., the greater the β) for a fixed value of $\overline{T}_W$, the smaller the difference between the flux densities emanating from the porous body in the isothermaland nonisothermal cases (the temperature of the isothermal layer is here assumed equal to the temperature at $z = {}^1/_2$ in the nonisothermal layer).

Results of computations obtained in the more general formulation, i.e., in the presence of external surfaces, are represented in Fig. 4 in the case $\overline{T}_0 = \overline{T}_W$ (the curves in Figs. 3 and 4 correspond to β = 28, ℓ = 50). It is seen from Fig. 4 that the curves $j(\varepsilon)$ are characterized by a maximum. As $\varepsilon \to 1$ the value of j tends to a quantity determined from (17), i.e., is independent of ε_0.

Therefore the approach proposed permits an analytic expression to be obtained for the radiation flux density emanating from a disperse layer in both the isothermal and nonisothermal cases. The value of j depends on the geometric characteristics of the system (porosity, particle size, layer thickness), the temperature distribution in the layer and the emissivity of the external surfaces and particles simulating the disperse system. The necessity to introduce and compute the effective coefficient permitting the nonisothermy of the emitting layer to be taken into account [2] hence drops out. Let us note that the relationships obtained can be utilized in estimating both the emissivity of aerodisperse systems and the radiation of porous layers in which there is a heat source (for example, the layer of a porous catalyst in which exothermal chemical reaction occurs). The dependences found afford the possibility, in principle, of estimating the parameters of the system under consideration according to the measured values of the radiation flux density emanating from the layer.

NOTATION

σ, is the Stefan-Boltzmann constant, Π, is the layer porosity, ε and ε_0 are the particle and external surface emissivities, and T_0 is the outer surface temperature.

LITERATURE CITED

1. J. Butterill, Heat Transfer in a Fluidized Bed [Russian translation], Moscow (1980).
2. V. A. Borodulya and V. I. Kovensky, Int. J. Heat Mass Trans., 26, No. 2, 277-287 (1983).
3. R. Ziegel, Heat Transmission [Russian translation], No. 3, 168-175 (1988).
4. Tien, Modern Machine Construction [Russian translation], Ser. A, No. 6, 139-154 (1989).
5. G. E. Gorelik, V. V. Levdanskii, V. G. Leitsina, and N. V. Pavlyukevich, Inzh.-Fiz. Zh., 50, No. 6, 999-1005 (1986).

6. V. V. Levdanskii, "Mathematical and Physical Questions of Heat and Mass Transfer [in Russian], 3-8, Collection of Scient. Research, Inst. Heat and Mass Transfer, Beloruss. Acad. Sci., Minsk (1973).
7. T. D. Sandry and F. D. Stevenson, J. Chem. Phys., 55, No. 8, 4150-4151 (1971).
8. B. V. Deryagin and S. P. Bakanov, Dokl. Akad. Nauk SSSR, 115, No. 2, 267-270 (1957).
9. E. M. Sparrow and R. D. Sess, Heat Transfer by Radiation [Russian translation], Leningrad (1971).
10. R. Ziegel and J. Howell, Heat Transfer by Radiation [Russian translation], Moscow (1975) (1975).
11. V. A. Borodulya, V. I. Kovenskii, and K. E. Makhorin, Heat and Mass Transfer in Disperse Systems [in Russian] Collection of Scientific Research, Inst. Heat and Mass Transfer, Beloruss. Acad. Sci., Minsk, 3-20 (1982).

NONLINEAR MASS TRANSFER BETWEEN A GAS AND A FALLING LIQUID FILM.

3. MULTICOMPONENT MASS TRANSPORT

Khr. Boyadzhiev

UDC 532.72:532.529

A solution is obtained for the problem of multicomponent mass transfer between a gas and a falling liquid film. The case is considered in which the mass transfer of one of the components is limited by the nonlinear mass transport in the gas phase. The rates of multicomponent mass transport in the gas and liquid phases are determined.

In the first and second parts of this work [1, 2] it was shown that nonlinear mass transfer (as a result of intensive mass transport in the gas phase) leads to significant changes in the velocity distributions in the liquid and gas. In the case of multicomponent mass transport this leads not only to changes in the rates of transport of the components with the large concentration gradients but also to changes in the rates of transport of the components for which the concentration gradients do not influence the hydrodynamics of the flow.

The literature contains a number of experimental studies [3-5] in which it has been shown that as a result of simultaneous mass transfer in gas-liquid and liquid-liquid systems the transport of one component leads to changes in the rates of transport of the others. In these cases an increase in the rate of mass transfer is usually observed which is caused by the Marangoni effect, since this cannot be explained using the linear theory of mass transport [6].

In the present paper the effect will be considered for the case of multicomponent mass transport for the case in which the concentration gradient of one of the components in the gas phase influences the hydrodynamics of the flow.

Mathematical Description. The theory of diffusion in multicomponent systems [7, 8] shows that the approximation of independent diffusion can be used not only in the case when the concentrations of the components are low, but also when the diffusion coefficients of the individual components are similar. This makes it possible to solve the problem of the kinetics of nonlinear mass transfer between a gas and a falling liquid film in multicomponent systems by solving the problem for the transport of any component to the approximation of the linear theory of mass transport, where the velocity distribution takes into account the effects of the nonlinear mass transport of one of the components.

Let $\bar{c}_1$ and c_1 be the concentrations of any component in the gas and liquid, where mass

Institute of Chemical Engineering, Bulgarian Academy of Sciences, Sofia. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 59, No. 4, pp. 593-602, October, 1990. Original article submitted January 23, 1989.

 0022-0841/90/5904-1272$12.50