

LAWS OF THERMAL DISINTEGRATION IN THE INTERACTION OF A BODY
WITH A HIGH-SPEED GAS FLOW

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Conditions for the stabilization of parameters characterizing the thermal disintegration of materials are established. Universal relations are obtained to calculate ablation rate within a broad range of external parameters.

The interaction of a body with a high-speed gas flow, being a complex pattern of gas-dynamic, physicochemical, and heat- and mass-transfer processes, is found upon closer examination to have a whole range of distinguishing features.

First of all, we should note the so-called "hypersonic stabilization" that takes place [1]. The essence of this phenomenon is that with an increase in the velocity of the external flow V_∞ or the Mach number of the incoming flow, the distribution of the gasdynamic and thermal parameters along the surface of the body approaches a certain constant, "stabilized" state. At $M > 10$, flow behind the shock wave turns out to be nearly self-similar, i.e., independent of the Mach number.

This is quite unusual if one considers that the pressure P'_0 and enthalpy I'_0 of the stagnated flow in this case continue to increase in proportion to the square of the velocity of the incoming flow

$$P'_0 = P + \frac{\rho_\infty V_\infty^2}{2}, \quad (1)$$

$$I'_0 = I + \frac{V_\infty^2}{2}. \quad (2)$$

There is a corresponding increase in the heat flux. For example, the heat flux in the neighborhood of the critical point with a laminar boundary layer is proportional to

$$q_0 \sim \sqrt{\frac{P'_0}{R_N}} I'_0.$$

If "hypersonic stabilization" makes it possible to limit oneself to $M < 10$ when studying the pattern of flow about bodies, then considerably slower flows can be used when modeling the thermal effects of high-speed flows - at least in the vicinity of the critical point. The use of slower flows here would involve an increase in the static component of stagnation enthalpy. In accordance with (2), this could be done by preheating of the gas [2].

The high level of thermal and mechanical action of the flow leads to an increase in the temperature of the immersed body and further absorption of heat due to different physicochemical changes occurring during the body's disintegration. The entire range of factors which figure into the mechanism of heat absorption during disintegration can be broken down into four groups of phenomena governed by their own laws: absorption of heat due to radiation from the surface; heat absorption due to the thermal effects of phase and physicochemical transformations; heat absorption due to the effect of blowing; heat absorption due to the transfer of heat to colder internal layers. The determination of each of these factors is a complex problem on its own [3]. Nevertheless, the authors of [4] proposed an empirical relation for the dimensionless rate of ablation of different thermally protective materials. With allowance for the data in [5], this relation can be written in the form

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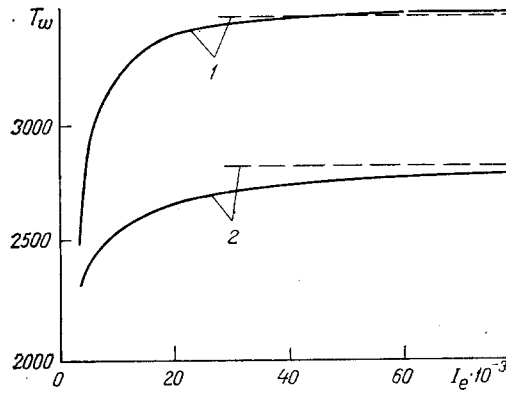


Fig. 1

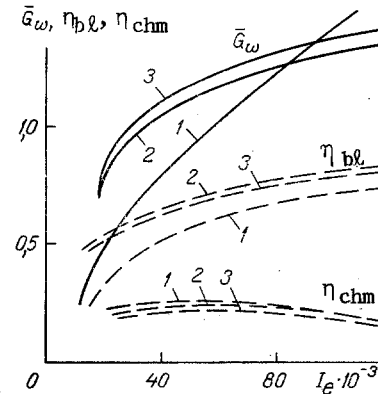


Fig. 2

Fig. 1. Dependence of the surface temperature of quartz glass on flow stagnation enthalpy: solid curves show results calculated from the model in [3]; dashed lines show estimates of the maximum value of T_w from Eq. (10); 1) $P_e = 10^6$; 2) 10^4 Pa. T_w , K, I_e , kJ/kg.

Fig. 2. Dependence of the dimensionless ablation rate and the relative fraction of the thermal effects of blowing η_{bl} and the chemical reactions η_{chm} in the heat balance on the disintegrating surface on flow stagnation enthalpy [6]: 1) sweating of quartz glass; 2) combustion of carbon on the surface; 3) heterogeneous reaction of quartz and carbon.

$$\bar{G}_w = \sqrt{\frac{I_e - I_w}{H}} - 0.3. \quad (3)$$

This relation has been substantiated by numerous experiments and by numerical calculations of the process of the disintegration of quartz glass in a laminar flow (blowing coefficient $\gamma \approx 0.6$) within the range of stagnation enthalpies $10^4 - 5 \cdot 10^4$ kJ/kg and stagnation pressures $10^4 - 10^7$ Pa.

However, it is known that the blowing coefficient γ is one-half to one-third lower for a turbulent flow regime than the laminar regime. Its value also depends heavily on the ratio of the molecular weights of the gas mixture at the surface of the body $\bar{\mu}_\Sigma$ and the vapor $\bar{\mu}_v$ [3]. The thermal pattern of the ablation process may also be complicated by the erosive entrainment of translucent material, combustion, and various technical factors. All of these effects should lead in varying degrees to an increase in the actual ablation rate.

The goal of the present study is to examine the conditions for stabilization of the parameters characterizing the thermal disintegration of materials, prove the generality of law (3), and evaluate its suitability for calculating ablation in the presence of complicating factors.

In connection with this, we will examine how ablation occurs with a sublimating substance. In accordance with the Knudsen-Langmuir equation, the ablation rate \bar{G}_w in this case is equal to:

$$G_w = \frac{\alpha(P_v^H - P_v)}{\sqrt{2\pi RT_w/\bar{\mu}_v}}. \quad (4)$$

Strictly speaking, (4) is valid only in the absence of foreign substances on the surface and for a low gas density in a vapor cloud $\bar{\mu}_v$.

To determine the unknown vapor pressure P_v , we use the mass balance at the boundary between the condensed and gas phases. We equate the mass flow rate G_w with the sum of the convective ($c_{v, w}, G_w$) and diffusion flows of sublimated particles:

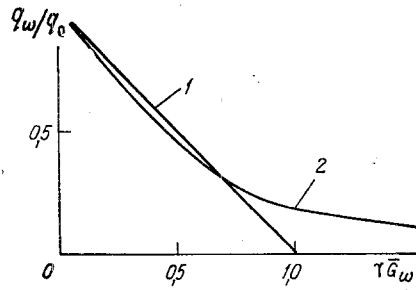


Fig. 3

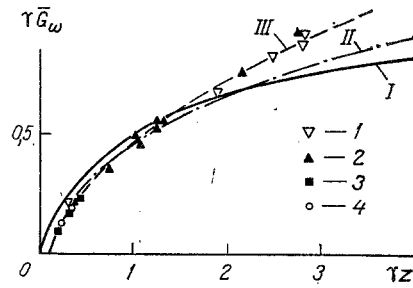


Fig. 4

Fig. 3. Comparison of linear (1) and quadratic (2) approximations of the effect of blowing.

Fig. 4. The dependence of $\gamma \bar{G}_w$ on the dimensionless enthalpy of the flow γz : I, II, III) calculations with (12), (13), and (14); points denote experimental results; 1) polytetrafluoroethylene, $H^* = 2750$ kJ/kg; 2) glass-plastic on an epoxy binder, $H^* = 10,700$; 3) alloyed quartz glass-ceramic, $H^* = 15,700$; 4) graphite, $H^* = 34,000$ kJ/kg.

$$G_w = c_{v,w} G_w - \beta (c_{v,e} - c_{v,w}). \quad (5)$$

We assume that the incoming flow does not contain species similar to the ablation products $c_{v,e} = 0$. Using the analogy between heat and mass transfer, we equate the coefficient β to the coefficient $(\alpha/c_p)_w = q_w / (I_e - I_w)$, where $I_e \approx I_0'$ is the enthalpy on the external boundary of the boundary layer.

The mass concentration of the vapor $c_{v,w}$ is connected with the partial pressure P_v and the molecular weights of the vapor and gas mixture at the surface of the body by the relation $c_{v,w} = \rho_v \bar{\mu}_v / (P_e \bar{\mu}_\Sigma)$. With allowance for these additional facts, we change Eq. (5) to the form

$$G_w = \frac{(\alpha/c_p)_w P_v \bar{\mu}_v}{P_e \bar{\mu}_\Sigma - P_v \bar{\mu}_v}.$$

The heat-transfer coefficient $(\alpha/c_p)_w$ changes in proportion to the ablation rate G_w with blowing of the sublimation products into the high-temperature boundary layer of the incoming flow.

We assume that the thermal effect of blowing can be described by a simple linear relation of the type obtained for a laminar boundary layer [3]:

$$(\alpha/c_p)_w = (\alpha/c_p)_0 (1 - \gamma \bar{G}_w) = (\alpha/c_p)_0 \left[1 - 0.6 \left(\frac{\bar{\mu}_\Sigma}{\bar{\mu}_v} \right)^{0.24} \bar{G}_w \right]. \quad (6)$$

In this case, the mass balance on the sublimating surface takes the form

$$\bar{G}_w = G_w / (\alpha/c_p)_0 = \frac{P_v \bar{\mu}_v}{P_e \bar{\mu}_\Sigma - (1 - \gamma) P_v \bar{\mu}_v}. \quad (7)$$

Simultaneously solving Eqs. (4) and (7), we can exclude the vapor pressure P_v and, with assigned values for the pressure on the external boundary of the boundary layer P_e , the heat-transfer coefficient $(\alpha/c_p)_0$, and the blowing coefficient γ , we can establish the dependence of ablation rate \bar{G}_w on the temperature of the surface of the body T_w . The relations $\bar{G}_w = f(T_w)$ in the pressure range $10^3 - 10^6$ Pa are presented in [3]. The character of these relations is connected mainly with the function $P_v^H(T_w)$. It is known that the saturation vapor pressure can be described by means of the Clausius-Clapeyron equation

$$P_v^H(T_w) = \exp \left[b - \frac{\Delta Q_v \bar{\mu}_v}{RT_w} \right]. \quad (8)$$

For a prescribed temperature of the surface of the body T_w , the limitingly possible sublimation rate occurs in a vacuum ($P_v = 0$) or in the presence of a chemical reaction on a sublimating surface which completely eliminates the vapor molecules and thus precludes condensation. In this case, ablation depends only on the temperature T_w :

$$G_w \rightarrow G_{\max} = aP_v^H(T_w) \left/ \sqrt{2\pi \frac{R}{\mu_v} T_w} \right. \quad (9)$$

According to (7), the actual ablation rate in a high-speed gas flow also depends on the pressure P_e and the heat-transfer coefficient $(\alpha/c_p)_\theta$. If the dimensionless ablation rate \bar{G}_w is not high, then the partial pressure of the gas cannot exceed the value $P_v < P_e \mu_\Sigma / [(1-\gamma)\mu_v]$. This makes it possible to obtain an estimate of the temperature of the disintegrating surface by replacing P_v by the saturation vapor pressure (8):

$$T_w \rightarrow T_{\max} = \frac{\Delta Q_v \bar{\mu}_v}{R [b - \ln \{P_e \mu_\Sigma / \mu_v (1-\gamma)\}]} \quad (10)$$

Figure 1 shows the results of calculation of the surface temperature of sublimating quartz glass and its maximum values calculated from Eq. (10). It is evident that there is no change in this temperature even at a flow stagnation enthalpy $I_e > 20,000$ kJ/kg. Meanwhile the estimate (10) both qualitatively and quantitatively satisfactorily accounts for the dependence of the surface temperature on pressure P_e . Here, the heat of sublimation ΔQ_v is equal to the heat of formation of quartz 8780 kJ/kg, not to the total thermal effect of the surface processes ΔQ_v . The latter additionally includes the effect of partial dissociation of SiO_2 molecules. The constant in Eq. (10) was given a value of 20.05 for quartz glass.

As was shown in [3, 6], the disintegration of thermally protective materials may be accompanied by a large number of different physico-chemical changes which in one way or another affect the rate of disintegration and surface temperature T_w . Thus, the evaluation of the maximum value of T_w from (10) should be complemented by the use of a relation which accounts for the possibility of the occurrence of chemical reactions on the disintegrating surface. Here, the additional relation should consider the vaporizing species and its role in the reactions.

It is evident from Fig. 2 that an increase in the enthalpy of the flow is accompanied by a difference in the chemical individuality η_{chm} of the disintegration models and an increase in the contribution of blowing η_{bl} to the heat balance [6]. There is also a rapid decrease in the role of the viscosity of the melt, and most materials are carried off in gaseous form at flow enthalpies above 20,000 kJ/kg. All this provides grounds for construction of a simplified scheme of ablation with a minimum number of controlling parameters.

Let us examine the heat valence on the disintegrating surface of a body which undergoes ablation mainly in gaseous form. Given sufficiently high levels of heating, we can ignore radiation from the disintegrating surface. We will also assume that the surface temperature is "stabilized." Thus, we can take a constant value for the parameter characterizing internal heat absorption $H^* = c(T_w - T_0) + \Delta Q_w = \text{const}$. We then obtain

$$q_0 = (\alpha/c_p)_0 (I_e - I_w) = \varepsilon \sigma T_w^4 + q_{\text{bl}} + G_w [c(T_w - T_0) + \Delta Q_w] \approx q_{\text{bl}} + G_w H^* \quad (11)$$

We now examine the effect of blowing in two approximations: linear $q_w/q_0 = 1 - \gamma \bar{G}_w$ and quadratic $q_w/q_0 = 1/[3(\gamma \bar{G}_w)^2 + \gamma \bar{G}_w + 1]$. Figure 3 compares these two approximations. It is evident that they begin to differ appreciably at $\gamma \bar{G}_w > 0.6$.

With a linear approximation of blowing, heat balance (11) reduces to the following equation to determine dimensionless ablation rate (more accurately, the product $\gamma \bar{G}_w$):

$$\gamma \bar{G}_w = \frac{\gamma (I_e - I_w)}{H^* + \gamma (I_e - I_w)} = \frac{\gamma z}{1 + \gamma z} \quad (12)$$

where $z = (I_e - I_w)/H^*$ is the dimensionless enthalpy of the flow.

In the limit at $z \rightarrow \infty$, the product $\gamma \bar{G}_w \rightarrow 1$, i.e., the dimensionless ablation rate cannot exceed $1/\gamma$. The greatest change in the complex $\gamma \bar{G}_w$ is seen in the range $0 < \gamma z < 1$. At $\gamma z > 1$, its derivative rapidly decreases in inverse proportion to the square of z .

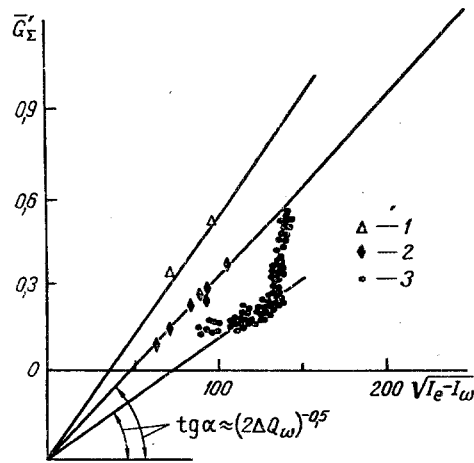


Fig. 5. Dependence of dimensionless ablation rate \bar{G}_w^1 on the square root of the enthalpy gradient: 1) quartz glass, calculation with (3); 2) alloyed quartz glass-ceramic (0.5% Cr_2O_3); 3) graphite, data from [8]. $\sqrt{I_e - I_w}$, $(\text{kJ/kg})^{0.5}$.

It follows from Fig. 3 that the linear approximation of blowing may yield sizable errors in the range $\gamma\bar{G}_w > 0.65$. We will therefore examine the heat-balance equation with a quadratic approximation of blowing. In this case, the equation reduces to a cubic equation in the complex $\gamma\bar{G}_w$:

$$3(\gamma\bar{G}_w)^3 + (\gamma\bar{G}_w)^2 + \gamma\bar{G}_w = \gamma z.$$

This equation has a single real root. Expansion into a series can be employed to find this root in the regions $\gamma\bar{G}_w > 0.65$ or $\gamma z > 1.5$ of interest to us (Fig. 4). Leaving only the linear term in the expansion, we ultimately obtain an equation for dimensionless ablation rate in the form

$$\gamma\bar{G}_w = \sqrt[3]{\frac{\gamma z}{3}} \left(1 - \frac{0.2}{\sqrt[3]{(\gamma z)^2}} \right) - \frac{1}{9}. \quad (13)$$

A check showed that the solution of the cubic equation in the form (13) is satisfactorily accurate at $\gamma z > 0.4$ (Fig. 4). Comparison of the complexes $\gamma\bar{G}_w$ for the linear and quadratic approximations of blowing in Fig. 4 shows that they agree well within the range $\gamma z < 3.0$. This indicates that we can take $\gamma(I_e - I_w) \leq 3H^*$ or $\bar{G}_w \leq 0.75/\gamma$ as the upper limit of the range in which the linear approximation of blowing is valid.

It was shown in [7] that the approximate relation $\Delta Q_w \approx 3.4c(T_w - T_0)$ is valid for pure substances and quartz glass in the sublimation regime. Using this relation and multiplying Eq. (3) by the coefficient γ , we convert it to a form analogous to (12) and (13):

$$\gamma\bar{G}_w = \sqrt{\gamma z \left(\frac{\gamma}{1.5} \right)} - 0.3\gamma.$$

For a laminar boundary layer, $\gamma \approx 0.6$. This allows us to make the further simplification:

$$\gamma\bar{G}_w \approx 0.63 \sqrt{\gamma z} - 0.18. \quad (14)$$

Comparison of experimental data (points 1-4 in Fig. 4) with solutions of differing accuracy in the form (12) and (13) and with Eq. (14) indicates the existence of a universal dependence of $\gamma\bar{G}_w$ on γz .

Thus, empirical relation (3) can be extended to any other conditions if the blowing coefficient γ differs little from the mean "laminar" value of 0.6 and if the ratio $\gamma z < 5$. (The

enthalpy I_e is no greater than $9H^*$ or $12\Delta Q_w$). Otherwise, it will be necessary to introduce a correlation for the difference in the quantity γ . In particular, such a correction will be necessary for the transition to turbulent flow in the boundary layer, when γ decreases by a factor of 2-3.

To check the degree of the effect of translucence of the materials and erosive entrainment on adherence to law (3), where

$$\bar{G}_w \approx \bar{G}'_z = G_z \frac{I_e - I_w}{I_e - I_{c.wa}}, \quad (15)$$

we conducted experiments to determine the ablation rate of quartz glass and we examined data on the destruction of an alloyed quartz glass-ceramic, a glass-plastic on an epoxy binder, and graphite. This data was obtained in [4, 5, 8]. Figure 5 shows the experimental data analyzed in the form (3) with allowance for (15).

It follows from this figure and from the results in [4] that neither the presence of a low-temperature species (the binder) nor the transparency of the material affect the linear character of relation (3). However, the heat of disintegration H , determining the slope of Eqs. (3) and calculable from the formula proposed in [9], is substantially lower than for an opaque material (alloyed quartz ceramic).

This conclusion is consistent with the data in [10], according to which the change in the optical properties of fused quartz may nearly double the rate of its disintegration.

As noted by the authors of [8], at temperatures above 3750 K, a significant amount of ATJ graphite begins to be carried off in the form of particles. As a result, the linear relation $\bar{G}'_z - f(\sqrt{I_e - I_w})$ sharply changes its slope (point 3 in Fig. 5). In this case, the heat of disintegration of graphite H is much lower than $2(\Delta Q_w)$. The diffusion regime of graphite oxidation seen at stagnation enthalpies up to 15,000 kJ/kg also increases the ablation rate compared to the result calculated from (3).

Thus, law (3) is observed in nearly all of the cases examined at $\bar{G}'_z > 0.5$ and $\gamma \approx 0.6$. Opaqueness of the material and erosive entrainment lead to a reduction in the heat of disintegration H compared to $2(\Delta Q_w)$. As the transparency of the surface layer of the material decreases, H increases and reaches its maximum value $\sim 2(\Delta Q_w)$.

NOTATION

V_∞ , M. velocity and Mach number of incoming flow; I'_0 , P'_0 , stagnation enthalpy and pressure of gas flow; ρ_∞ , density of incoming flow; I , P , static components of stagnation enthalpy and pressure; q_0 , incoming heat flux; R_N , radius of curvature of body in the neighborhood of the critical point; I_e , P_e , enthalpy and pressure on the external boundary of the boundary layer; G_w , dimensionless rate of vaporization; H , heat of disintegration of the material; ΔQ_w , thermal effect of phase and physicochemical transformations on the surface; γ , blowing coefficient; μ_Σ , μ_v , molecular weights of the gas mixture near the surface of the body and of the vapor; P_v , partial pressure of vapor above the surface of the body; $P_v^s(T_w)$, saturation vapor pressure; G_w , vaporization rate; a , accommodation coefficient; R , universal gas constant; T_w , surface temperature; I_w , enthalpy of gas at the temperature of the surface of the body; c_v , e , c_v , w , mass concentration of vapor in the incoming flow and at the disintegrating surface; β , diffusion coefficient; $(\alpha/c_p)_0$, $(\alpha/c_p)_w$, heat-transfer coefficient without and with allowance for the effect of blowing; q_w , heat flux minus the blowing effect; b , empirical constant; ΔQ_v , heat of sublimation; ϵ , emissivity; σ , Stefan-Boltzmann constant; q_{bl} , thermal effect of blowing; c , heat capacity; T_0 , ambient temperature; H^* , internal heat absorption; $I_{c.wa}$, enthalpy of gas at the temperature of the "cold wall."

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ALLOWANCE FOR PARTICLE ROUGHNESS IN DESCRIBING
RADIATIVE TRANSFER IN AN AEROSOL

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A model of the propagation of thermal radiation in an aerosol containing rough opaque particles is proposed within the framework of a diffusion approximation for total radiation.

The kinetic equation for thermal radiation in an aerosol contains the radiative characteristics of the particles: absorption efficiency factor Q_a , scattering factor Q_s , scattering indicatrix $p_s(\theta)$. These quantities depend on both on the state of the particle surface and on particle size and shape and the complex refractive index $m = n - ik$ of the substance comprising the particles. They are calculated in accordance with the Mie theory [1, 2] for spherical particles (for which the deviation of Δ from ideal sphericity due to microroughness is small $\Delta \ll R$). The theory was subsequently extended to include optically smooth particles ($\Delta \ll \lambda$, [3, 4]). There are no recommendations on calculating Q_a and Q_s for rough particles ($\Delta \geq \lambda$). There are studies in which the authors have attempted to allow for particle roughness, however. The radiative transport equation was solved in [5] for a gas suspension of coal dust. The suspension contained "gray" particles with a size no smaller than 40 μm . Here, it was assumed that $Q_a = \epsilon$, $Q_s = 1 - \epsilon$, while the form of p_s was postulated. The relationship between the proposed method of describing the radiative properties of particles and the widely-used method based on the Mie theory was not discussed in [5]. The authors of [5] also did not indicate the range of application of the approximation. The authors of [6-8] examined spherical particles of coal with a radius $R \geq 10 \mu\text{m}$. The value of Q_a determined from the Mie theory was used in the calculations performed in [6-8], while Q_s was assumed to be equal to $Q_s = 1 - \epsilon$. In the determination of the indicatrix in [6-8], it was assumed that the surface of the coal particles was very rough. For the characteristic wavelengths of thermal radiation corresponding to temperatures $T \geq 1600 \text{ K}$, the diffraction parameter $X = 2\pi R/\lambda \gg 1$. In this case, the scattered radiation can be divided into diffracted and reflected parts. The diffracted component is concentrated in a narrow solid angle near the direction of the incident beam. This makes it possible to assume that it is not scattered from the beam. The reflected component for an opaque particle is determined by the condition of its surface. In the case of a very rough particle, the direction opposite the direction of the incident beam is dominant for scattering [9]. Thus, it was assumed in [6, 7] that $p_s = 1 - \cos \theta$. As a result, it can be concluded that the approach used in [6-8] is elective. In this approach, Q_a was calculated from the Mie theory on the one hand, while on the other hand the roughness of the particle surface was considered in calculating the indicatrix. It follows from this that the question of the radiative properties of rough particles remains unanswered.

The goal of the present investigation is to use a diffusion approximation to obtain an equation for the total radiant flux in a gas suspension of opaque rough particles for the plane-parallel case. By allowing for the roughness of the particle surface, we increase the