DETERMINATION OF EFFICIENCY LOSSES IN GAS SUSPENSIONS

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Equations for calculating the efficiency losses in a polydisperse gas suspension which are due to chemical reactions, diffusion, thermal and mechanical interactions between phases, etc., are obtained by the methods of nonequilibrium thermodynamics.

Gas suspensions are used as heat- and mass-transfer agents in complex processes of power technology, in the thermal treatment of metals and disperse materials, etc. [1-4]. The necessity therefore arises for the thermodynamic evaluation of the efficency of such processes. This can follow the course of finding the corresponding efficiency losses [5].

Let us consider a gas suspension consisting of n gas components and solid particles. Among the gas components there are r possible chemical reactions.

Let us determine the efficiency losses in such a gas suspension.

The efficiency losses in any system can be calculated by the equation [5]

$$\Delta E = T_0 \Delta S. \tag{1}$$

The entropy rise ΔS in a system with a volume V in a time τ is determined by the equation [6]

$$\Delta S = \int_0^\tau d\tau \int_V \sigma dV.$$

Therefore, (1) takes the form

$$\Delta E = T_0 \int_0^\tau d\tau \int_V \sigma dV. \tag{2}$$

Consequently, it is necessary to calculate σ for a gas suspension with allowance for the fact that because of the interaction of the phases the entropy increases to a greater extent in it than in a pure gas.

Let us make several assumptions. There are no chemical reactions or mass exchange between the gas and the particles, the particles have the same sizes, and collisions between particles are not taken into account. We consider the model of continuous interacting media of [7] to be valid.

The Gibbs equations for each of the phases are [8]

$$T_{\mathrm{g}} \frac{dS_{\mathrm{g}}}{d\tau} = \frac{du_{\mathrm{g}}}{d\tau} + p_{\mathrm{g}} \frac{dw_{\mathrm{g}}}{d\tau} - \sum_{k=1}^{n} \mu_{\mathrm{cg}} \frac{d\nu_{\mathrm{cg}}}{d\tau}, \tag{3}$$

$$T_{\mathrm{p}} \frac{dS_{\mathrm{p}}}{d\tau} = \frac{du_{\mathrm{p}}}{d\tau}. \tag{4}$$

We find the variation in internal energy for each of the phases from the equations [9]

$$\rho_{\mathrm{g}} \frac{du_{\mathrm{g}}}{d\tau} = -\nabla, \mathbf{I}_{\mathrm{g}} - \mathscr{P}_{\mathrm{g}} : \nabla \mathbf{v}_{\mathrm{g}} + \sum_{k=1}^{n} \mathbf{I}_{\mathrm{cg}} \cdot \mathbf{F}_{\mathrm{cg}} + \beta_{\mathrm{g}} (e_{\mathrm{a}} - e_{\mathrm{s}})_{\mathrm{g}} - q + \chi_{\mathrm{g}} \mathbf{f} (\mathbf{v}_{\mathrm{g}} - \mathbf{v}_{\mathrm{p}}) + N\eta, \tag{5}$$

$$\rho_{\mathrm{p}} \frac{du_{\mathrm{p}}}{d\tau} = -\nabla, \mathbf{I}_{u\mathrm{p}} + q + \beta_{\mathrm{p}} (e_{\mathrm{p}} - e_{\mathrm{s}})_{\mathrm{p}} + \chi_{\mathrm{p}} \mathbf{f} (\mathbf{v}_{\mathrm{g}} - \mathbf{v}_{\mathrm{p}}), \tag{6}$$

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where
$$\mathbf{I}_{cg}=\rho_{cg}(\mathbf{v}_{cg}-\mathbf{v}_g);\quad \mathscr{P}_g=\beta_p p_g U+\Pi_g;\quad q=\frac{\alpha}{c_g}(h_g-h_\pi)\omega N.$$

In writing (6) it is kept in mind that $\mathscr{P}_p = 0$ for a gas suspension [7].

Substituting Eq. (3) into Eq. (5) and (4) into (6), we perform the usual transformations [6] and then add the results. We finally obtain expressions for the entropy production in a monodisperse gas suspension:

$$\sigma=\sigma_g+\sigma_p=-\frac{1}{T_g^2}\mathbf{I}_{ug}\cdot\nabla T_g-\frac{1}{T_p^2}\mathbf{I}_{up}\nabla T_p-\frac{1}{T_g}\sum_{k=1}^{n}\mathbf{I}_{cg}\left(T_g\nabla\frac{\mu_{cg}}{T_g}-\mathbf{F}_{cg}\right)-$$
$$-\frac{1}{T_g}\Pi_g:\nabla\mathbf{v}_g-\frac{1}{T_g}\sum_{i=1}^{r}A_{gi}L_{gi}+\frac{1}{T_g}\beta_g(e_a-e_s)_g+$$
$$+\frac{1}{T_p}\beta_p(e_a-e_s)_p+q\left(\frac{1}{T_p}-\frac{1}{T_g}\right)+\frac{1}{T_g}\chi_g\mathbf{f}(\mathbf{v}_g-\mathbf{v}_p)+\frac{1}{T_p}\chi\mathbf{f}(\mathbf{v}_g-\mathbf{v}_p)+\frac{N\eta}{T_g}.\qquad(7)$$

Here $\mathbf{I}_{ug}=\mathbf{I}_{qg}=-\beta_g\lambda_g\Delta T_g$; $\mathbf{I}_{up}=\mathbf{I}_{qp}=-\beta_p\lambda_p\Delta T_p$.

The first and second terms on the right side of Eq. (7) are due to heat transfer in the respective phases, the third term is connected with the diffusion of the gas components, the fourth is determined by the gradients in the velocity field of the gas medium, the fifth is due to chemical reactions between the gas components, the sixth and seventh terms are determined by radiant heat exchange, the eighth is connected with interphase heat exchange, the ninth and tenth are due to the dissipation of the energy of macroscopic motion into the internal energy of the respective phases owing to viscous forces, and the last term is connected with the dissipation of the energy of fine-scale pseudovortical motion into the internal energy of the gas.

When there is a discrete size distribution of the particles, the respective terms of Eq. (7) are written for each class j of the set of particles of a single size. Therefore, the equation for the entropy production in a polydisperse gas suspension is

$$\sigma=\sigma_g+\sum_{j=1}^{m}\sigma_j^{4}=-\frac{1}{T_g^2}\mathbf{I}_{ug}\cdot\nabla T_g-\sum_{j=1}^{m}\frac{1}{T_{pj}^2}\mathbf{I}_{upj}\cdot\nabla T_{pj}-$$
$$-\frac{1}{T_g}\sum_{k=1}^{n}\mathbf{I}_{cg}\cdot\left(T_g\nabla\frac{\mu_{cg}}{T_{cg}}-\mathbf{F}_{cg}\right)-\frac{1}{T_g}\Pi_g:\nabla\mathbf{v}_g-$$
$$-\frac{1}{T_g}\sum_{i=1}^{r}A_{gi}L_{gi}+\frac{1}{T_g}(e_a-e_s)_g+\sum_{j=1}^{m}\frac{\beta_{pj}}{T_{pj}}(e_a-e_s)_{pj}+$$
$$+\sum_{j=1}^{m}q_j\left(\frac{1}{T_{pj}}-\frac{1}{T_g}\right)+\frac{1}{T_g}\sum_{j=1}^{m}\chi_{gj}\mathbf{f}_j(\mathbf{v}_g-\mathbf{v}_{pj})+\sum_{j=1}^{m}\frac{\chi_{pj}}{T_{pj}}\mathbf{f}_j(\mathbf{v}_g-\mathbf{v}_{pj})+\sum_{j=1}^{m}\frac{N_j\eta_j}{T_g},\qquad(8)$$

where m is the number of classes of particles of a single size.

Of course, the use of Eqs. (2) and (8) for the thermodynamic analysis of a concrete process by the well-known methods of [5], such as by the entropy method, requires the incorporation of additional physical considerations characterizing this process. As an example, let us find the efficiency losses due to interphase heat exchange during the compression (expansion) of a monodisperse gas suspension. We assume that there are no chemical reactions, the particles are of spherical shape of radius R, and the thermal resistance of the particles is small. It is necessary to deal with such a problem in calculations of gas-turbine installations in which a gas suspension is used as the working substance [2].

With the assumptions enumerated above, from (8) we obtain

$$\sigma=q\left(\frac{1}{T_p}-\frac{1}{T_g}\right)=\alpha\omega N\frac{\Delta T^2}{T_gT_p},$$

where $\Delta T = T_g = T_p$.

After substituting the latter equation into (2), we have

$$\Delta E = T_0 \alpha\omega N V \int_0^{\tau} \frac{\Delta T^2}{T_g T_p}\, d\tau. \tag{9}$$

Suppose the gas changes its temperature instantaneously to a certain value T_{2g} while the particles change their temperature during a time τ. Then the quantity ΔT is determined by the dependence [10]

$$\Delta T = |\Delta T_1| \exp\left(-\frac{\tau}{\tau_p}\right),$$

where $\Delta T_1 = T_{2g} - T_{1p}$ is a constant quantity; $T_{1p} = T_{1g}$ is the particle temperature, equal to the gas temperature before the start of compression of the gas suspension; $\tau_p = \rho_p^0 c_p R/3\alpha$ is the particle relaxation time.

We calculate the integral

$$\int_0^{\tau} \frac{\Delta T^2}{T_g T_p}\, d\tau \simeq \int_0^{\infty} \frac{\Delta T_1^2 \exp\left(-\frac{2\tau}{\tau_p}\right)}{T_{2g}\left[T_{2g} - \Delta T_1 \exp\left(-\frac{\tau}{\tau_p}\right)\right]}\, d\tau$$

$$= \frac{\tau_p}{T_{2g}}\left[-\Delta T_1 - T_{2g} \ln\left|1 - \frac{\Delta T_1}{T_{2g}}\right|\right] \simeq \frac{\tau_p}{2}\left(\frac{\Delta T_1}{T_{2g}}\right)^2.$$

Following [10], in the integration we assume that $\tau \to \infty$, since $\tau \gg \tau_p$. The result of the integration is expanded in a power-law series. In doing this we are confined to the first two terms of the expansion.

Finally, (9) takes the form

$$\Delta E = T_0 \alpha\omega N V \left(\frac{\Delta T_1}{T_{2g}}\right)^2 \frac{\tau_p}{2} = T_0 M_p \left(\frac{\Delta T_1}{T_{2g}}\right)^2 \frac{c_p}{2}.$$

If it is assumed in addition that $T_{1g} \gg \Delta T$, then we obtain the result of [10].

In conclusion, we note that the relations obtained here make it possible to perform calculations of complicated composite processes for the purpose of finding their optimum parameters.

NOTATION

n, number of gas components; r, number of chemical reactions; E, efficiency; τ, time; T, temperature; T_0, ambient temperature; S, entropy; σ, entropy production per unit volume of mixture per unit time; V, volume; β, bulk concentration; ρ, average density; ρ^0, true density; **v**, velocity; p, pressure; u, internal energy; w, specific volume; μ, chemical potential; γ_c, relative concentration of gas component; I_u, internal energy flux; ∇, Hamiltonian operator; $d/d\tau$, substantial derivative operator; **P**, stress tensor; U, unit matrix; Π, viscous stress tensor; $\mathbf{I}_{cg}$, diffusion flux; $\mathbf{F}_{cg}$, external force; e_a, absorbed radiation of medium; e_s, self-radiation of medium; q, interphase heat flux; α, heat-exchange coefficient; c, heat capacity; ω, particle surface; hg, h_π, enthalpy of gas mixture at a distance from a particle surface and at it, respectively; N, number of suspended particles per unit volume; **f**, force connected with difference in velocities between phases; χ, coefficient showing the fraction of dissipated kinetic energy of the mixture which changes directly into the internal energy of a phase; η, dissipative function due to fine-scale gas motion around inclusions; A_{gi}, chemical affinity of i-th chemical reaction; I_q, heat flux; λ, thermal conductivity coefficient; j, number of classes of solid particles of the same sizes; R, particle radius; M, mass. Indices: g, quantities pertaining to the gas; p, quantities pertaining to the particles.

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EFFECT OF THE INHOMOGENEITY OF THE GRANULAR CHARGE IN WATER-PURIFYING FILTERS ON THE INCREMENT IN THE HEAD LOSSES DURING COLMATATION

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The results of some experimental investigations into the relationship between the increment in the head losses of the colmatizing granular charge of a water-purifying filter and its degree of inhomogeneity are presented.

Granular filters are widely employed in preparing water for industrial and drinking purposes. Regulation of the structure of the granular bed (granulometric composition, height, microgeometry of the grains, etc.) is one of the chief ways of improving efficiency. Thus, Martensen's proposal [1] to replace quartz sand by crushed lightweight aggregates of various classes having a high intergranular porosity and a well-developed grain surface increased the productivity of ordinary filter constructions [2, 3] by a factor of two or three times and led to the development of new and more perfect systems [4]. In order to make the best possible use of the advantages of the new filter materials it is essential to develop a reliable method of calculating their properties, and, in particular, a method of choosing the optimum inhomogeneity of the bed with respect to grain size.

According to Mints and Krishtul [5, 6] the increment in the head losses of a silting, inhomogeneous charge during the separation of low-concentration suspensions is given by $\Delta h = h_0 \varphi \gamma T_c$, where $T_c = t d_{eq}^{0.5} x^{-1}$, $d_{eq} = \sum_{i=1}^{N} p_i d_i$. As regards charges of quartz sand, it was found that the size inhomogeneity of the grains could conveniently be represented by a power function:

$$\varphi = R^{-2}, \tag{1}$$

where $R = d_{0-20} d_{eq}^{-1}$ is the inhomogeneity coefficient. The quantity d_{0-20} is obtained from a granulometric analysis of the charge. It is here assumed that during the periodic regeneration of the charge in a rising water flow with a 40-50% expansion of the bed a strict classification of the grains is made with respect to geometrical size (in the normal operation of a system of washing-water distribution this requirement is met by quartz sand).

It was shown earlier that lightweight aggregate grains were classified less sharply than quartz in the course of regeneration [7]. This is because of the complex microgeometry of the aggregate grains and also their variable density — the crushing operation is applied simultaneously to the fused crusts and swollen mass of the aggregate gravel. Under these conditions the use of Eq. (1) in calculating filters with a lightweight aggregate charge fails to satisfy engineering requirements. In order to improve the equation we undertook some experiments based on the method described in [6].

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