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REPLY TO STARKOV'S COMMENTS ON THE ARTICLE: "CALCULATING THE FLOW OF A TWO-PHASE STREAM IN AN AXISYMMETRIC SUPERSONIC NOZZLE"

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In the derivation of the system of equations, Starkov objects to our assumption that no heat transfer takes place between phases. We resorted to this assumption not in order to reduce computer machine time, as concluded by Starkov, but to ascertain the effect of an exclusively mechanical action (the friction of the gas against the particles) on the progress of a two-phase flow in a nozzle. Consideration of the effect of heat transfer clouds the issue. In our paper we have presented a system of equations both with and without consideration of heat transfer. Here, however, on the basis of computer calculations, it is demonstrated that consideration of heat transfer leads to but a slight change in the adiabatic efficiency of the discharge process and in the specific impulse, as referred to the gas phase.

The equation of motion for a solid particle, recommended by Starkov, is a special case of the one given in our paper. The coefficient c_x in our equation is a function of $\mathrm{Re}_{\mathrm{rel}}$, where

$$\mathrm{Re}_{\mathrm{rel}} = \frac{(w_g - w_s)\, d_g \gamma_g}{\mu_g g}.$$

Here we assumed that

$$\text{for} \quad \mathrm{Re}_{\mathrm{rel}} < 5.8 \quad c_x = \frac{24}{\mathrm{Re}_{\mathrm{rel}}},$$

$$\text{for} \quad 5.8 \leqslant \mathrm{Re}_{\mathrm{rel}} \leqslant 730 \quad c_x = \frac{13}{\sqrt{\mathrm{Re}_{\mathrm{rel}}}},$$

$$\text{for} \quad \mathrm{Re}_{\mathrm{rel}} > 730 \quad c_x = 0.48.$$

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Thus the formula recommended by Starkov describes only the motion of particles in the region of laminar particle streamlining, where the resistance is determined according to Stokes's law. Using this equation to describe the region $Re_{rel} \geq 5.8$ leads to a gross error, since in this region dw_g/dx is not proportional to $[(w_g/w_s) - 1]$. To be fair, is should be pointed out that here we used the data from the streamlining of a single sphere in a gas flow. According to the data of [1], in the transition and turbulent regions the relationship between the resistance factor and the Re_{rel} number for a system of moving spherical particles will differ from the analogous function for a single sphere in a gas flow.

Since Starkov did not understand how we derived the second equation in system (3), probably because we failed adequately to detail the transformation of system (1) to the form of (3), we will again present the derivation of this equation. Let us introduce the speed of sound as $a^2 = dp_g/d\gamma_g$. Substituting this expression dp/dx from the momentum equation of system (1) into the continuity equation, we obtain the condition for the inversion of the effect in the form

$$\frac{dw_g}{dx} = \frac{1}{M^2 - 1}\left(\frac{w_g}{F}\frac{dF}{dx} - \frac{g_s}{g_g} M^2 \frac{dw_s}{dx}\right).$$

It was not the purpose of our article to describe the methods involved in the numerical calculation, and in particular, the passage of the point M = 1, since this method is sufficiently well known. One of the sources [2] in which the method for the passage of the point M = 1 is cited in the Starkov article.

As regards the specific impulse, in certain cases it is convenient to refer it to the gas phase. This makes it possible to more completely describe the essential nature of the process. It is clearly indicated in our paper that the specific impulse is referred to the gas phase.

In conclusion, it should be pointed out that, unlike other papers, in our article we present an evaluation of the effect exerted by the transfer of heat between the phases on the efficiency of the discharge process for the two-phase flow and that the specific impulse is referred to the gas phase; we have introduced the concept of an adiabatic efficiency for the discharge process of the two-phase flow and we indicate the relationship of this coefficient to the weight composition of the two-phase flow and to the dimensions of the particles; analysis of the conditions for the inversion of the effect and of the executed calculations provides the basis for an explanation of the influence exerted by the particle dimensions and the weight composition of the two-phase flow on the magnitude of the shift in the critical cross section in the diverging portion of the nozzle; on the basis of the calculational results we provide a qualitative explanation for the experimental data of Komov [3].

These are our thoughts in connection with the problems touched on in the article by Starkov.

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REPLY TO STARKOV'S COMMENTS ON THE ARTICLE: "THE FLOW OF A GAS–LIQUID MIXTURE IN A SHAPED NOZZLE, WITH A CONSTANT PHASE VELOCITY DIFFERENCE"

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In a number of papers dealing with the study of gas flows with particles in rocket nozzles (including the works of Hassan and Kliegel, cited by Starkov), the equations governing the nature of the energy

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