On the interphase and intra-phase interaction of particles and gas in a layer of granular materials behind shock wave

S V Poplavski
Khristianovich Institute of Theoretical and Applied Mechanics, Novosibirsk, 630090 Russia

E-mail: s.poplav@itam.nsc.ru

Abstract. The work is devoted to the analysis of physical mechanisms of lifting a layer of granular material in the flow behind shock wave. Based on experimental data physical processes are considered behind a shock wave traveling above a dust layer, leading to its rise: the escape of single particles from the layer and the formation of an intermediate layer or fluidized bed between a dense layer and a suspension, the collision of particles in the fluidized bed and its ascent, the influence of a dense suspension on the flow behind the shock wave, and the effect of unsteady flow on the rise of the layer. A physical model of the process is proposed that allows predicting the rate and height of the rise of a layer of granular material at an early stage of interaction with the flow behind incident shock wave.

1. Introduction
Lifting particles from the dust layer in the flow behind the shock wave (SW) is an important item within the dust explosion problem. There are many experimental and theoretical works on this subject, but there is still no single physical model of the process. This was the case in 1984 [1], the same was asserted twenty years later [2]. At present, a number of mechanisms for lifting the layer are known, which are not connected by a single theory. Models of the layer lifting can be divided into two groups. In the first one, it is assumed that bulk materials are a continuous medium. In the framework of this approach, the following is considered: 1) the development of compression waves in the layer (not confirmed); 2) instability of the surface of the layer; and 3) formation and growth of a turbulent two-phase mixing layer [1, 2]. The second group includes models that consider only vertical forces acting on the particle in the flow, namely 1) the force associated with the velocity difference at the particle size in the shear flow (the Saffman effect) [3], 2) the force caused by the rotation of the sphere in the flow (Magnus effect) [4], and 3) transverse momentum acquired by particles in collisions in a dense suspension [4, 5]. In favor of these mechanisms is the fact that they explain the rise of the layer without the SW, which is indeed the case, while against these mechanisms is the fact that they do not explain the primary emission of particles from the layer. Thus, behind the SW sliding over a layer of bulk material, various physical mechanisms for lifting particles are realized, whose role can be estimated as follows:

- None of these mechanisms explains the rise of the layer independently without involving other effects;
- None of these mechanisms takes into account processes in the gaseous phase behind the SW over the layer and in the layer of bulk material;
- Each of these effects can make a different contribution at different stages of the process;
- And, finally, each of these mechanisms is realized within the limits of its physical limitations, but all of them are possible with some mobility of the particles over the resting layer.

This state of granular materials, known as the fluidized bed, is possible with the supply of external energy, for example, with a vertical blowing of gas through a layer of granular material, and in this case from tangential stress in the sliding flow and in the intra-phase exchange of the particles momentum in the layer. In this regard, the granular bed lifting, interphase and intra-phase interaction in dense dust clouds are topical to consider together. The aim of this work is to analyze and generalize the physical mechanisms of interphase and intraphase interaction of particles with respect to the questions of lifting a layer of granular material in the flow behind incident shock wave.

2. The rise of single particles behind the shock wave
The experiments were performed on a shock tube UT-4M ITAM SB RAS with a channel section 52×52mm in the measuring chamber and quartz windows 20×200 mm for shadow registration. At the micro level, the primary rise of the layer is well modeled by single particles. In this study, experiments performed with large carbon particles of irregular shape (up to 1.5 mm) and with spherical organic glass particles with \( d \sim 200 \mu m \). The dynamics of the particles recorded by a high-speed shadow method with an interval between frames of 50 microseconds. Experiments have shown that spherical particles behind the SW roll along a smooth wall, but do not rise. Although the direction of rotation of the sphere when rolling in a flow is favorable for the positive Magnus effect, it does not appear, and that's why. The Magnus force is comparable with the gravitational force at some optimal ratio of flow velocity and rotation speed. For particles with \( d \approx 200 \mu m \) in a stream with a velocity of 660 m/s, the rotation frequency should be \( f \approx 10^4 \) s\(^{-1}\) [4]. For a rolling sphere at an early stage of acceleration, the relative velocity of the stream is maximal, but the angular velocity of rotation is small, and at a late stage, the relative velocity of the sphere and the flow is too small.

Single particles of irregular shape under the same conditions break away from the wall, but before they also begin to roll. The features of the rolling of a non-spherical particle, apparently, determine their rise. Figure 1 shows shots from a series of shadow images of a rarefied monolayer of coal particles behind the SW. Particles behave differently, which is due to differences in mass and shape. So, the particle (1) rolls, but for 450 µs it still does not break away from the wall. The particles (2) and (3) rotate in the rolling direction and rise at a speed of \( \sim 5-7.5 \) m/s. For these particles, the rolling stage is not recorded, but this is done for the particle (4), which on the frame No. 5 rolls under the action of the flow, and on frames No. 7 and 9 it rises at a vertical speed of \( \approx 6 \) m/s.

![Figure 1. Raising of the rarefied monolayer of single particles of irregular shape at the moments of 250, 350 and 450 µs after the passage of the shock wave front; the SW Mach number \( M_s = 1.54 \), the gas velocity \( u_2 = 260 \) m / s, the scale is set by the reference points at the top of the frame (interval 10mm).](image-url)

This mechanism of particle lifting, first described in [6], is based on the vertical vibration of the center of mass of a non-spherical particle during its rolling. When the acceleration of oscillations with
amplitude $\Delta = D - d$ ($D$ and $d$ is the maximum and minimum size) exceeds $g$ (the gravitational constant), the nonspherical particle breaks away from the smooth wall, or the spherical particle - from the surface of the layer with a roughness $\equiv \Delta$. Parametric analysis showed that the rise in this mechanism occurs at a rolling speed $v_x \geq v_{cr} \geq 3\sqrt{dg}$, and the initial vertical velocity $v_y \geq 0.3v_x$. These estimates are quite plausible at a qualitative level, the critical velocity $v_{cr}$, (and the delay of separation with it), actually grow nonlinearly with increasing particle size. However, it can also be seen from the experiments that the actual separation velocity is higher than $v_y$. This is because the estimates are obtained for rigid kinematic coupling of particles to the wall, but because of the sliding of the particles along a smooth wall, the rotation and particles take-off begins at a velocity $v_x$ greater than $v_{cr}$. However, the agreement of the estimates and observations becomes good for the roughness of the wall $\equiv \Delta$, which corresponds to the state of the surface of the layer of granular material. A similar mechanism for the particles takeoff was proposed in [7]. Thus, the features of the rolling of non-spherical particles or spheres over a rough surface can be considered as the primary mechanism of particles entering the flow and forming a fluidized bed. Further, the evidence of its existence will be given.

3. Lifting the layer of granular material in the flow behind the shock wave

The experiments on lifting the dust layer behind the shock wave performed in the shock tubes cover only the initial stage of the process because of the duration restriction of the plug of the constant flow parameters $\equiv 0.5\text{-}1$ ms. Nevertheless, it is at this stage that a two-phase mixing layer is formed as well the conditions for its growth above the deposition of dust. Polydisperse samples of coal dust with different layer thicknesses and roughness were used in the experiments. In all cases, the layer was placed on a smooth channel wall with a smoothed leading edge. Figure 2 shows a typical series of shadow images obtained in an experiment with coal dust with a particle size $d \leq 100 \mu m$, SW Mach number $M_s = 1.54$. A layer of brown coal was studied in the form of a track $\equiv 10$ mm wide under the following conditions: gas velocity behind the shock wave front $u_2 = 260$ m/s, layer thickness 2-3 mm, interval between frames 50 μs. The layer had a natural roughness, and the leading edge was at the boundary of the observation region.

Figure 2. Shadow registration of the initial stage of interaction of SW with a layer of coal dust; SW Mach number is $M_s = 1.54$, the interval between frames is 50 μs, gas velocity behind SW front $u_2 = 260$ m/s, the dashed line shows the channel wall.

The dynamics of the rise of the layer was studied at two points, where the front of the shock wave was located in the frames 1 and 2, these points were chosen from the considerations that they have the exact zero of time. The average rate of ascent at two observation points is close to 5 m/s. The effect of the leading edge on the measurement of the height of the layer disappears at a length of 30 mm. This is due to the limitations of the shadow method and the inability to register individual particles over the boundary of a dense suspension, which are indisputably present there due to the deflection of the flow. However, even without an estimate of the concentration above and below the suspension boundary, it is clear that most of the dust is contained below the transparency boundary in a dense suspension.
determination of the suspension boundary and the parameters of the dust system below will be obtained in the next section.

To estimate the effect of particle collision, the "collision" Stokes number $\text{Stk}_c=\tau_p/\tau_c$ is used, where $\tau_p$ is the time of particle velocity relaxation, $\tau_c$ is the average interval between collisions. Instead of the values of $\tau_p$ and $\tau_c$, we can use the length of the velocity relaxation $\lambda=4\rho_p d/3\rho C_a-10^3d$ [5,6] and the mean free path $R$: $\text{Stk}_c=\lambda/R \approx 10^3d/R$. At $\text{Stk}_c \ll 1$, the particles between collisions restore the relaxation degree with the flow and move as solitary. Such dust systems are referred to as dilute suspension. In the other limiting case $\text{Stk}_c \gg 1$, the time between collisions is small in comparison with the time constant of the velocity relaxation, the intra-phase exchange of the momentum leads to a randomization of particle velocities, and their velocity in the flow direction is comparable with the transverse component. This state of the dust-system is called a dense suspension, and its parameters are shown below.

4. Parameters of a dense suspension and collision of particles in a fluidized bed

The existence of a transition state between a suspension and a granular layer is indicated by an estimate of the concentration of particles above it. For quantitative studies of the layer lift dynamics, the boundary of the transparency of the suspension (BT) was chosen. The volume concentration of particles $\beta_c$ at this boundary is determined from the "transparency" $\varphi=s_j/s$ in this region of the shadow image with area $s$, from which the area $s_j$ is occupied by particles. With the known optical thickness of the object $L$ and the particle diameter $d$

$$\varphi = \left( sL\beta \left( \frac{\pi d^2}{4} \right) \right) \left( \frac{\left( \pi d^2/4 \right)}{s} \right), \quad \text{then} \quad \beta = \frac{2}{3} \frac{\varphi}{L} \frac{d}{\lambda}. \quad (1)$$

At the transparency boundary, $\varphi = 1$, the concentration is $\beta_c = 2d/3L$. In our experiments, $L = 10^2$ m, $d = 100 \mu m$, $\beta_c = 10^2$. This is the threshold concentration above which the slurry is transparent, and below the BT ($\beta_c > 10^3$) $10^3 \leq \beta \leq 0.71$. Thus, the observed rise of particles behind the SW from the bulk state is the growth of the thickness of the fluidized bed, where the concentration varies more than by 70 times (from 0.71 to $10^5$) at a thickness of 1-3 mm. This state of a dispersed medium is conveniently described by statistical parameters: the average distance between the particles, the mean free path, and the collision parameters. These characteristics are considered in detail in [5], but here we give only finite formulas and estimates. So, the average distance between the centers of particles is

$$\sigma = \frac{1}{d} = \sqrt{\frac{\pi \sqrt{2}}{6\beta}} \arcsin \left( \frac{2}{3} \frac{0.71}{\beta} \right). \quad (2)$$

At $\beta_c \approx 10^2$, the distance between the particles is $\sigma \approx 1 \sim 3$, and the mean free path is a little more, the exact expression for this parameter is given in [5]. According to the symmetry, adopted in [5], each particle is surrounded by 12 chaotically moving particles. These particles form a spherical cluster with a central particle inside it. With respect to the central particle, they are a "near" circle, which, according to [5], can leave it only at an average distance $\sigma = l/d > \sqrt[3]{3}$, i.e. for $\sigma < \sqrt[3]{3}$ ($\beta > 0.14$), the mean free path is $R \approx \sigma d$. This particular case of estimating $R$ shows the possibility of determining the mean free path differently than in the kinetic theory of gases through the frequency and velocity of collisions where the size of the molecules is neglected. A more general approach is to find the radius of the spherical layer $R$, in which, for a given concentration $\beta$, there are enough particles so that the central particle, moving in an arbitrary direction, collides with a probability of 100%.

The probability of collision with particles from an elementary spherical layer is $dW = W_i(r)dn$, where $W_i(r)$ is the probability of collision with one particle at a distance $r$, $dn$ is the number of particles in a spherical layer of radius $r$ and thickness $dr$: $dn = 24\beta(\gamma_d^2)^2d(\gamma_d)$. The probability of collision with one particle is the ratio of the bodily angle of the cross section of the pair collision to the total bodily angle $W_i(r) = 1/(4\pi)\arcsin(d/r)$. Introducing the substitution $d/r = x$, we obtain the form of the particle collision probability function over the length $\sigma \leq 1/x \leq R/d = r$. 

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\[ W(R) = -\frac{24}{\pi} \beta^{\frac{3}{2}} \arcsin(x) x^4 \text{ d}x \]

The mean free path \( R \) is found from the condition \( W(R) = 1 \). The complete equation for the collision probability (3) has no solution in algebraic form, and was solved numerically in [5]. It is shown that the solution of equation (3) at \( 0.14 < \beta < 0.7 \) satisfies the condition \( r \equiv \sigma \). In [5], an approximate probability equation was also obtained for \( \arcsin(x) \approx x \) при \( x << 1 \):

\[ W(r) \approx \frac{8}{\pi} \beta \left( r^2 - \sigma^2 \right) = 1 \text{, then } r = \frac{R}{d} \left[ \sqrt{\frac{\pi}{8\beta}} + \left( \frac{0.71}{\beta} \right)^{\frac{1}{3}} \right] \]

Comparison (4) with the "exact" solution of the probability equation (3) showed good agreement at \( k = 0.77 \). Despite the limitation of \( x << 1 \) in the expansion of \( \arcsin(x) \approx x \) (large distances between particles, small concentrations) function (4) proved to be suitable within a wide range of concentrations of \( 10^{-3} < \beta < 0.7 \).

It is also shown that, at a concentration \( \beta \approx 0.5–1\% \) (the transparency limit of the suspension), the dimensionless free path length \( R/d \approx 5–7 \). Then the collision Stokes number \( \text{St}_c = \lambda/R = 10^3 d/R > 10^2 \), which corresponds to a dense suspension with a pronounced effect of particles collisions on transport phenomena in a two-phase flow in the longitudinal and, in particular, transverse directions. A "ballistic" model was proposed in [6], which describes well the observed rate of rise of the layer by the particles collision mechanism in a fluidized bed.

5. On the influence of a dense suspension on the flow behind a shock wave sliding over layer of dust

The inverse effect of the dispersed phase on the flow behind the SW is well known, it is expressed in the inhibition of gas in a particle cloud and is explained by the interphase exchange of the momentum in the early stage of the phase’s velocity relaxation. At supersonic conditions, the braking of the flow is accompanied by additional heating of the gas with increasing pressure [8], which increases the danger of dust explosions. In [8], a physical model of the nonstationary flow behind the shock wave in a dust particle is proposed, which makes it possible identifying the determining physical parameters of the process. Here, the gas stopping effect is of interest as one more mechanism for the appearance of a transverse particle velocity component due to the transverse spreading of gas from a region of suspension with a high concentration. This is seen in figure 3, where the first 100 \( \mu \text{s} \) of interaction between a sample of powder material and SW was recorded by the multi-frame shadow recording method.

Figure 3. A cloud of plexiglas particles in the flow behind SW; the volume concentration of the dispersed phase is \( \beta \approx 3 \times 10^{-2} \); SW Mach number \( M_s = 4.5 \), interval between frames \( \Delta t = 20 \mu \text{s} \).
At the initial moment, the sample had a bulk density and was thrown to the level of the channel axis before the arrival of the shock wave front. In the suspended state, the powder concentration is estimated as $\beta \approx 3 \times 10^{-2}$ at the transparency boundary, its volume on frame No.1 is somewhat larger than the initial volume, although the shape of the "tablet" is preserved. In the future, the sample received the form of a "cometary trace" for two reasons: 1 transverse expansion of particles with gas due to a transverse pressure gradient; 2 the velocity of the gas and particles at the periphery is substantially greater due to the retardation of the flow on the axis of the cloud of particles with an increased concentration.

The axis of the sample is shown as a dotted line on frame No.6 and is associated with the channel wall in figure 2. Indeed, the gas braking effect at the leading edge of the bulk powder layer also results in deflection of the flow with the removal of particles to the periphery. This analogy is also reinforced by the fact that the velocity of peripheral particles is much higher than the velocity in a dense layer, causing the area above it to quickly emerge from the outgoing particles, as shown by the "comet trace" in figure 3. The flow of gas-permeable three-dimensional bodies with erosion and changing form has not been studied up to now, and the dynamics of particles of irregular shape in the gradient flow behind the SW seems to be a promising problem for such systems [9, 10].

6. Conclusion
The main processes behind a shock wave traveling above a bed of granular material are considered, leading to its rise. These processes concern the escaping of single particles from the layer and forming an intermediate layer or fluidized bed between the dense layer and suspension, the collision of particles in the fluidized bed and its ascent, effect of a dense suspension on the flow behind the shock wave, and the influence of flow nonstationarity on the rise of the layer. For the first time, a physical model of the process is formulated that allows to predict the rate and height of the layer of granular material in the flow behind the shock wave at a quantitative level.

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