

## Quasithermal Effects During Rapid Gravity Flow of a Granular Medium

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### Abstract

The investigation results of granular temperature during rapid gravity flow of granular medium on a rough chute are discussed. The granular temperature is determined as the kinetic energy of several forms of mutual displacements of particles. The influence of the chute angle on the value ratio of different components of granular temperature is analyzed. The components of granular temperature induced by fluctuation, shear and transversal mutual displacements of particles were taken into account.

### Keywords

Granular medium; rapid gravity flow; granular temperature; shear rate; void volume fraction.

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The physics of granular materials (“granular matter”) is one of the main branches of the physics of condensed matter (“soft condensed matter”) [1], which has now evolved into a rapidly developing interdisciplinary field of knowledge with a huge number of applications. Properties of granular materials are so special that, depending on the dynamic conditions of their existence, they can be identified as a solid, gas or liquid, endowed with unusual properties, which indicates their mesoscopic nature.

Fast gravity flows are one of the most common forms of shear flows of granular materials in natural phenomena and technological processes. The corresponding natural phenomena significantly affect the relief of the Earth’s surface (basal currents, rockfalls, mudflows, dunes). In technological processes involving this kind of materials, fast gravity flows are formed on natural slopes and inclined surfaces in heap storage facilities and transport devices, as well as in the working volumes of equipment, silos and supply bins in chemical, food, mining and processing, agricultural, metallurgical and many other industries. A characteristic feature of fast gravity flows is the presence of fast shear deformation of the granular medium. In this case, the stresses in the shear flow are formed mainly as a result of the exchange of particles by impact pulses through the shear surface. Such

dynamic conditions for the interaction of particles in short-term point contacts are fundamentally different from the conditions for contact of particles in a “slow” quasi-plastic shear flow. Under the conditions of a quasi-plastic shear flow, the interaction of particles proceeds with relatively enduring contacts, which occur mainly in the regime of sliding and rolling friction.

The high intensity of interaction of particles in fast gravity flows of granular materials becomes the reason [1–3] of a vivid manifestation of the effects of separation and mixing. The spontaneously occurring effects of separation and mixing of inhomogeneous particles significantly affect the kinetics of technological processes and natural phenomena. In accordance with the results of many studies, for example [3, 4], to predict the effects of separation and mixing of inhomogeneous particles in a fast gravity flow, it is necessary to have detailed information at the micro level about its kinematic and structural characteristics. This is all the more important if we take into account that, in accordance with the results of recent studies, the structural heterogeneity of the structural and kinematic parameters of a fast gravity flow is the reason for the manifestation of specific effects of the separation of inhomogeneous particles [3, 5]. It is obvious that in the absence of detailed information on the structural and kinematic parameters

of the flow, it is fundamentally impossible to provide a sufficiently accurate prediction of the dynamics of the distribution of inhomogeneous particles, and the analysis of the physical mechanisms of their interaction becomes extremely difficult.

A large number of works are devoted to the theoretical and experimental study of fast gravity flows of granular materials, for example [6–11]. However, many authors, for example [3, 12], note that despite the great scientific and practical interest in the study of gravity flows, there are still no sufficiently complete constitutive relations for their mathematical description. This is an obstacle to the development of a general model of the dynamics of fast gravity flows [8–11].

The problem of formulating the constitutive relations is largely associated with the complexity of expressing the dependence of the dynamic characteristics of the interaction of particles, their kinetic energy of chaotic oscillations and rotation on the angles and velocities of their collision. Due to this situation, there is still a high demand for reliable experimental data on the dynamics of fast gravity flows. Reliable detailed information about the structural and kinematic parameters of the flow is necessary not only for verification of mathematical models of flows, but also analysis of the physical mechanisms of the effects of separation and mixing of particles.

To describe the dynamics of shear flows of granular materials, two main groups of methods are used. Discrete element methods describe the dynamics of a flow as a result of analyzing the behavior of its individual particles, taking into account their interactions in a certain limited population. The methods of this group are mainly used in the analysis of granular media under conditions that allow the possibility of idealizing the factors of internal and external influence on individual particles. Discrete element methods are widely used, for example, to simulate experimental results [3, 11].

Alternative methods for studying the dynamics of shear flows are based on the representation of a granular medium as a continuum. The features of the continuous methods indicate the appropriateness of their use for describing the dynamics of flows formed in complex boundary conditions, for example, geophysical flows on surfaces of complex shapes [9, 10]. However, the models of the dynamics of gravity flows based on the continual approach, as a rule, use the assumption of the incompressibility of the granular medium and the structural homogeneity of its flow. This kind of assumption fundamentally limits the prognostic capabilities of the corresponding

mathematical models, since it does not allow reflecting the relationship of structural and kinematic parameters along the flow depth. Obviously, models with such restrictions cannot be used to obtain a complete set of information on the structural and kinematic parameters of the gravity flow with high heterogeneity over the layer thickness [3, 10]. Gravity flows with high inhomogeneity are formed in a thin-layer flow of granular materials [2]. In some works, for example [8, 11], the opinion is expressed that the development of an adequate description of the dynamics of gravity flows with high inhomogeneity can be facilitated by mathematical models constructed using phenomenological relations. Such relationships will make it possible to establish the relationship between the structural and kinematic parameters of shear flows in granular media. However, the development of such models is only in the very early stages.

When describing the dynamics of a fast shear flow of a granular medium, the phenomenological approach presupposes extensive use of the physical analogy between the chaotic motion of particles and the thermal motion of molecules. With such an analogy, it becomes possible to use a well-developed kinetic theory to describe the dynamics of fast shear flows. At present, a fairly large number of research results have been accumulated [5, 6, 13–16], which allow us to assert that the dynamics of fast shear flows of granular media is in many respects similar to molecular gas dynamics. This is confirmed by the results of successful use in many works [5, 6, 13, 17–20] of the main provisions of the kinetic theory of gas for solving problems of the dynamics of fast shear flows of granular materials.

By adapting the Goodman-Cowan model of a fast shear flow of granular materials [17], based on the fundamental principles of continuum mechanics, a model of the dynamics of a fast gravitational particle flow along a rough chute was developed in [18]. Subsequently, taking into account the obvious shortcomings of continuous medium models in [6, 13, 19, 20], the development of models of a fast gravity flow is carried out taking into account individual effects of particle interaction at the microlevel. As a result of analyzing the effect of momentum transfer in the course of collisions of particles and solving the system of equations describing the conservation of momentum and the energy of particle fluctuations, the authors of the listed works determined the stress tensor.

However, when analyzing the problem, the authors were forced to make assumptions that can lead to significant errors in describing the flow dynamics. The errors of description were clearly manifested in the

numerical simulation of the dynamics of the gravity flow on the chute, carried out in the framework of [21]. In the same work, the authors of [21] clearly demonstrated that adequate modeling of the flow dynamics using the developed models requires an adequate formulation of boundary conditions, which, in the general case, are extremely difficult to identify.

The authors of [13], based on the geometric analysis of the microstructure of the shear flow, concluded that a significant transverse mass transfer (quasi-diffusion) of particles should take place in the gravity flow. Assuming the effect of transverse mass transfer on the flow dynamics to be significant, the authors point out the need to take it into account when determining the conditions for the interaction of particles in a shear flow and come to the conclusion that the conditions of collision of particles are independent of the concentration of the solid phase in the shear flow of the material. Most of the models of particle interaction mechanisms in fast shear flows are based on a similar assumption. However, the absence of a dependence of the conditions of collision of particles on the concentration of the solid phase seems to be a very rough assumption that limits the possibilities of the approach proposed by the authors to the microstructural analysis of the dynamics of interaction of particles. This conclusion is confirmed by the results of a study [22], in which the discrete element method was used to simulate a fast shear flow of cohesionless inelastic spherical particles. One of the most important results of this study is the conclusion that the effective coefficient of friction, defined as the ratio of shear stress to normal stress, depends on the concentration of the solid phase. It was found that, depending on the volume fraction of voids in the shear flow, the conditions (angles) of collision of particles change, which is confirmed by the results of an experimental study obtained in [6].

In [20, 23], a physical parameter called the temperature of a granular medium ("granular temperature") was used to assess the intensity of chaotic movements of particles and their influence on the flow dynamics. The temperature of the granular medium is defined as a physical parameter, the value of which is proportional to the square of the mean value of the velocity of chaotic movements (fluctuations) of particles.

In [24], the dynamics of particle flow in a fast shear flow was modeled using the basic provisions of the theory of Brownian motion of molecules in liquids. When developing a mathematical model, it was assumed that the forces acting on a particle are proportional to its speed and the amplitude of chaotic

displacements. Obviously, this assumption limits the possibility of using the obtained model to describe the flows of granular materials with a high concentration of the solid phase.

The author of [25] came to the conclusion that there is a relationship between pressure, temperature of a granular medium and its viscosity, which is expressed in the form of the corresponding equation of state of a granular medium during its fast shear flow.

It is important to note that in all analyzed models of the dynamics of shear flows of granular media, the influence of the rotational component of the motion of particles on the dynamics of their interaction is neglected. The study of the role of the component of particle rotation in the dynamics of a fast shear flow was carried out in [26]. The results of the study led to the conclusion about the insignificant effect of particle rotation on various flow parameters, including the particle collision frequency, dispersion pressure, and many other parameters. However, along with this, it was found that at a low temperature of the granular medium, i.e. in a flow with low shear rates, the influence of rotation on the dynamics of a shear flow of a granular medium becomes significant.

In [27], an equation of state for a granular medium is proposed for a fast shear gravity flow. The equation establishes the relationship between the temperature of the granular medium, its lithostatic pressure and dilatancy (an increase in the volume fraction of voids). The authors of the work define the temperature of a granular medium as the kinetic energy of particles, which they acquire as a result of participation in mutual chaotic movements in a shear flow. The use of the equation of granular medium state to determine the structural and kinematic parameters of the gravity flow on a rough chute confirms its rather high prognostic capabilities. However, in [7], on the basis of an analysis of the circumstances that complicate the use of the kinetic theory for solving practical problems with respect to granular media, it was concluded that the named theory in its applied aspect needs significant development.

In the current circumstances, experimental methods for studying the structural and kinematic parameters of fast shear flows are of great importance, which provide the possibility of obtaining relevant information about the flow at the microlevel. The availability of detailed experimental information on the local values of the structural and kinematic characteristics is necessary for the development of mathematical models of flow dynamics, assessment of their adequacy, and study of the effects of particle interaction. However, on the way of experimental study

of fast gravity flows of granular materials, considerable difficulties arise. For example, the authors of [12] analyze the problem of experimental study of the structural and kinematic parameters of fast gravity flows on a rough chute and point to its extreme complexity, despite the apparent simplicity of the problem. Until now, there remains a need for experimental methods for determining the full complex of local values of the structural and kinematic parameters of gravity flows. An analysis of experimental methods for studying such flows indicates [6, 21] that the main difficulties in the experimental determination of local flow parameters are a consequence of extremely high disturbances during internal sounding and large boundary effects that significantly limit the possibilities of visual research methods.

The listed problems initiated the development of new alternative experimental methods for studying fast gravity flows based on the use of various types of penetrating radiation. The authors of [28] have successfully applied the tomography method using an X-ray scanner to study the distribution of non-uniform particles in the flow of granular material when it is unloaded from the hopper. However, the authors note the exceptional complexity of the application of the method they used to study the microstructural characteristics of the flow.

To study the microstructure of a dense layer of solid particles, the authors of [29] used magnetic resonance imaging. In [30], the authors used the methods of gamma densitometric tomography and electrical impedance tomography to study the distribution of components in a vertical three-phase flow. However, even in these cases, when using research methods with the use of various types of penetrating radiation, the determination of local microstructural characteristics of fast gravity flows turns out to be problematic.

To solve a wide range of scientific and practical problems, the method of computed tomography has now become widespread. For example, in [31], the authors carried out a computed tomography study of the gravity flow of particles, which is formed when unloading granular material from the hopper. A Siemens Somatom Plus X-ray computed tomograph was used to study the dynamics of the formation of the flow boundaries in the discharge channel of the bunker. However, despite the uniqueness of the method and equipment used, the authors did not find it possible to adapt the method they used to study the local microstructural parameters of the flow.

In [27], an experimental-analytical method is proposed for determining the local values of velocity and porosity (volume fraction of voids) in a fast gravity flow of granular materials on a rough chute. Among the important advantages of the method, one should highlight the possibility of its parallel use to study the effects of interaction of non-uniform particles in a fast gravity flow. In accordance with the method, experimental information is obtained by organizing a steady gravity flow of granular material on a rough chute, made in the form of a rectangular channel, and collecting falling particles into a horizontal cuvette, divided by transverse partitions into cells.

Experimental information includes the height of the layer  $h$  at the chute threshold, the angle  $\alpha$  of its incline, the time  $t$  of cuvette filling, the distribution function of the mass of the falling particles  $G(x_1)$  along the cells (along the corresponding horizontal coordinate  $x_1$ ), and the height  $H$  of the location of the chute threshold above the cells. Information on the local particle velocity and void fraction in the gravity flow on a rough chute is obtained by analytical processing of experimental data. The analysis allows one to determine the profiles of the velocity  $u(y)$  and the volume fraction of voids  $\varepsilon(y)$  in the layer of material on the slope based on the distribution of particles over the cells in the cuvette. The equations connecting the profiles  $u(y)$ ,  $\varepsilon(y)$  and the function  $G(x_1)$  in a fast gravity flow of particles on a rough chute are written in the following form:

$$|\vec{u}| = \frac{x_1 - y \sin \alpha}{\cos \alpha \sqrt{(H + y \cos \alpha - (x_1 - y \sin \alpha) \tan \alpha)^2 - \frac{2}{g}}}; \quad (1)$$

$$u(y(x_1))\rho(1 - \varepsilon(y)) = G(x_1). \quad (2)$$

Equations (1) and (2) only indirectly determine the unknown profiles  $\varepsilon(y)$  and  $u(y)$ . To introduce definiteness, dependences (1) and (2) are supplemented by the equation of state of a granular medium, which establishes the relationship between the local values of void fraction and shear rate ( $du/dy$ ). The equation of state is formulated on the assumption of a physical analogy between a granular medium at fast shear and a dense gas, which is established in the form of the well-known equation of gas dynamics. The equation determines the relationship between dilatancy  $\bar{\varepsilon}(y)$ , lithostatic pressure  $p(y)$  and the temperature of the granular medium  $E$  in the following form:

$$p \bar{\varepsilon} = \chi E, \quad (3)$$

where  $p(y) = \int_{h-y}^h \rho(1-\varepsilon(y))g \cos\alpha dy$  is lithostatic

pressure;  $\bar{\varepsilon}(y) = \frac{\varepsilon(y) - \varepsilon_v}{1 - \varepsilon(y)}$  is dilatancy of a granular

medium shear flow;  $\varepsilon_v$  is volume fraction of voids in a fixed bed;  $\chi$  is coefficient of the state equation of a granular medium;  $E(y)$  is temperature of the granular medium, which is defined as the specific kinetic energy of particles, which they possess due to various forms of their mutual displacements.

When determining the temperature of a granular medium, three types of kinetic energy of mutual displacements of particles were taken into account [32]: due to chaotic fluctuations  $E_{fl}$ , relative shear  $E_{sh}$  and transverse mass transfer  $E_{tr}$ :

$$E = E_{sh} + E_{fl} + E_{tr}. \quad (4)$$

The kinetic energy of particles due to their fluctuation is expressed in the following form:

$$E_{fl} = \frac{1}{2}\rho(V')^2, \quad (5)$$

where  $V'$  is mean velocity of particle fluctuations, which is calculated as a function of shear rate, void fraction, and particle properties [33, 34]. The shear component of the kinetic energy of particles is defined as

$$E_{sh} = \frac{1}{2}\rho(bd)^2 \left( \frac{du}{dy} \right)^2, \quad (6)$$

where  $d$  is mean particle diameter;  $b$  is geometric parameter, which is calculated as a function of porosity [27]. The specific kinetic energy of particles due to their transverse mass transfer in a shear flow is calculated as

$$E_{tr} = \frac{1}{4}\rho s \dot{V}' \frac{du}{dy}, \quad (7)$$

where  $s$  is the mean distance between particles, which is determined as a function of their diameter and void fraction [27, 34].

Equations (1), (2) and (3), taking into account expression (4) – (7), form a closed system with respect to the functions  $u(y)$ ,  $\varepsilon(y)$ ,  $y(x_1)$  and  $p(y)$ . The boundary condition for this system of equations is formulated as the condition for the “sticking” of particles to a rough chute if their coordinate along the layer height turns out to be zero ( $y = 0$ ), i.e.

$$u(0) = 0; y = 0. \quad (8)$$

Technically, this condition is ensured by making the surface of the chute with a roughness equal to half the diameter of the largest particles of the granular medium. The solution of the system of equations (1) – (3) and (8) is obtained by a numerical method using successive approximations [35].

It is obvious that the effectiveness of the described experimental-analytical method is directly determined by the adequacy of the equation of state of a granular medium at a fast shear (3). The proofs of the adequacy of the equation of state (3) were obtained both indirectly and directly. An indirect confirmation of the adequacy is the possibility of using the obtained structural-kinematic characteristics for adequate mathematical modeling of the distributions of the concentrations of non-uniform particles in a fast gravity flow [2, 5, 16, 27, 34]. Direct experimental confirmation of the adequacy of the equation of state (3) was obtained in [36] by the method of X-ray photography.

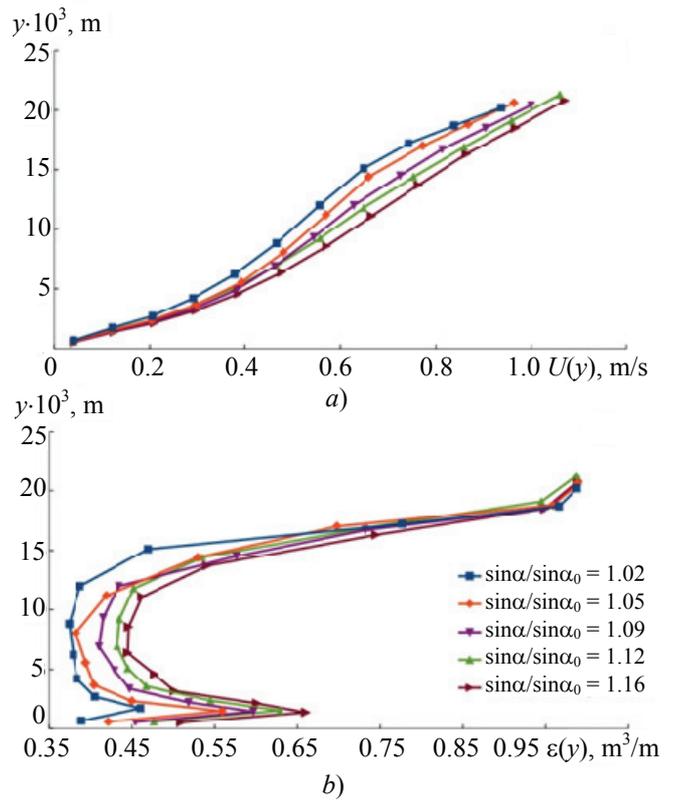
The most important physical parameter that determines the state of the granular medium during rapid shear is the temperature of the granular medium. In the stated version of its representation, the temperature reflects the total kinetic energy (4) of various forms of mutual relative displacements of particles. Thus, there is only a formal analogy between the temperature of the granular medium and the classical thermodynamic temperature. In contrast to thermodynamic temperature, which is a scalar isotropic parameter, the temperature of a granular medium is characterized by alternative properties. In particular, the results of the study carried out in [37] indicate the anisotropic properties of the temperature of the granular medium, and the nature of the anisotropy depends on the parameters of the external dynamic action on the granular medium and its physical and mechanical properties.

To a certain extent, the property of anisotropy of the temperature of a granular medium is reflected in the described method for determining it as a multicomponent parameter, the components of which have a specific spatial orientation. It is assumed that the temperature component due to chaotic fluctuations of particles does not have any dominant orientation in space. However, according to the results of studies [22], there is a dependence of the most probable angle of collision of particles in the region of high values of their concentration in the flow, which indicates a certain conventionality of the assumption. Strictly speaking, the assumption of a uniform spatial distribution of particle fluctuations is quite justified only for low particle concentrations in the shear flow.

A pronounced anisotropy is characteristic of the components of the temperature of the granular medium due to the presence of transverse mass transfer and relative velocity between particles to the shear direction in the gravity flow. In this case, for the first of the components, the transverse orientation dominates, and for the second, the longitudinal orientation is most probable. The stated structure of the temperature of the granular medium makes it possible to take into account the effect of dynamic conditions of varying complexity on the state of the bulk material in the shear flow. In this work, the temperature of a granular medium and its components in a fast gravity flow on a rough slope is investigated depending on the intensity of the shear gravitational action. The study was carried out using the described experimental-analytical method. The model material in the study was glass beads of fraction 3.5 – 3.75 mm. In the course of the experiment, with a change in the chute angle, a constant specific material consumption per unit length of the chute threshold was maintained, equal to  $0.95 \text{ kgm}^{-1}\text{s}^{-1}$ .

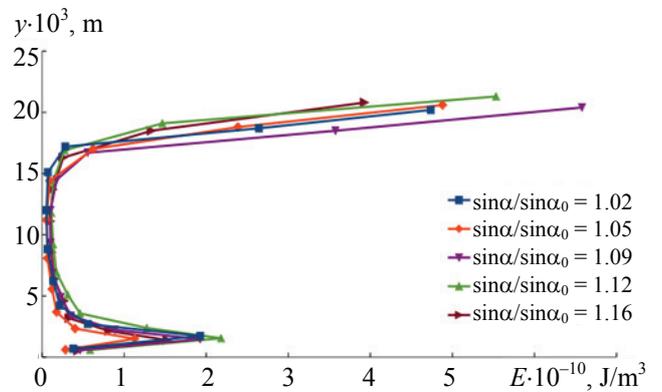
Figs 1a, b show the profiles of velocity and void fraction in fast gravity flows of beads at various relative values of the chute angle, which was defined as  $\sin\alpha/\sin\alpha_0$ , where  $\alpha_0$  is the angle of repose of the material. The presented profiles have a shape characteristic of this kind of flows [2, 5, 16, 27, 34], which is explained by the intense shear of the medium near the base of the layer and the formation of a rarefied cloud of particles near the open surface of the flow.

Fig. 2 shows the temperature profiles of the granular medium for gravity flows at different angles of inclination of the rough chute. First of all, attention is drawn to the high degree of analogy between the temperature and void fraction profiles (Figs. 1b and 2). The observed analogy is a consequence of the direct dependence of the dilatancy of the flow on the temperature of the granular medium in accordance with the equation of its state (3). In this case, an increase in temperature from the center of the layer to the base is explained by an increase in the shear rate, which, in accordance with expressions (5)–(7), directly determines the value of all temperature components. The sharp increase in temperature in the region of the layer adjacent to the open flow surface is a consequence of the combined effect of an intense increase in dilatancy and relatively high values of the shear rate. In conditions of high shear rate and large distances between particles, all types of mutual displacements of particles are maintained at high levels of relative velocities, which is reflected in high values of the components of the temperature of the granular medium.



**Fig. 1. Profiles of velocity (a) and void fraction (b) in a fast gravity flow of glass beads at different angles of inclination of the rough chute**

The profiles shown in Fig. 2 indicate a significant dependence of the temperature on the angle of inclination of the rough slope. Taking into account the high inhomogeneity of the flow and the complex shape of the profiles of local values of the temperature components, the dependences of their mean integral values on the gravitational effect were used for the analysis. The average integral values of temperature and its three components are determined using the following relationship



**Fig. 2. Profiles of local values of the temperature of a granular medium in a fast gravity flow of glass beads at different angles of inclination of a rough chute**

$$E_j = \frac{\sum_1^n E_{ji} u_i \Delta y_i (1 - \varepsilon_i)}{\sum_1^n u_i \Delta y_i (1 - \varepsilon_i)}, \quad (9)$$

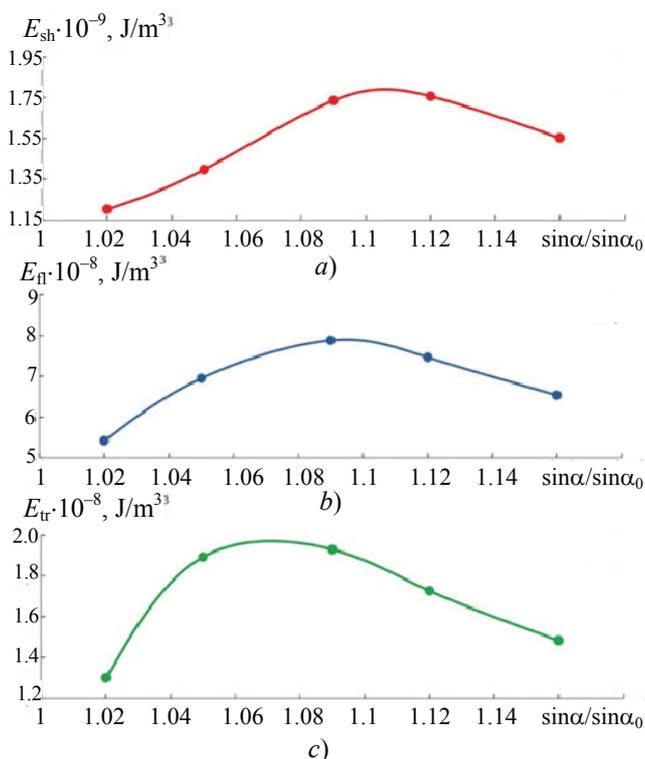
where  $i = 1, \dots, n$  is elementary sublayer number in the flow;  $u_i$  is average flow velocity in the  $i$ -th sublayer;  $\Delta y_i$  is  $i$ -th sublayer thickness;  $\varepsilon_i$  is mean void fraction of the  $i$ -th sublayer;  $E_{ji}$  is mean value of temperature  $E$  or one of its components ( $E_{sh}, E_{fl}, E_{tr}$ ) in the  $i$ -th sublayer.

Fig. 3 shows the dependences of the mean integral values of the temperature components on the angle of inclination of the rough chute. The representation of the chute angle in the form of the relative value of its functions ( $\sin\alpha/\sin\alpha_0$ ) is a reflection of the magnitude of the tangential gravitational force initiating the granular shear flow. The dependences shown in the figure indicate that with an increase in the shearing force in the region of small slope angles, it contributes to an intense increase in the effect of “heating” of the gravity flow. However, at slope angles corresponding to the value  $\sin\alpha/\sin\alpha_0 = 1.08 - 1.12$ ,

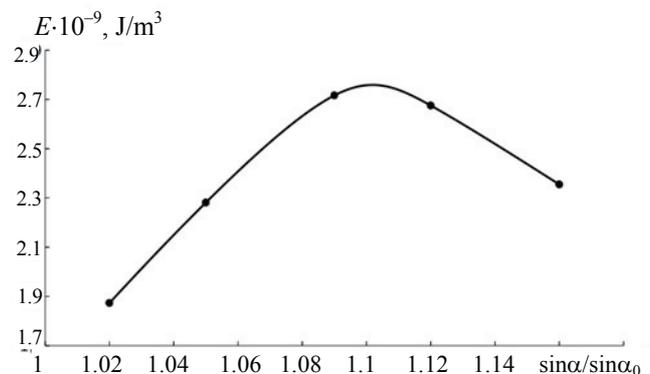
the components of the temperature of the granular medium reach a plateau of limiting values and, with a further increase in the angle, their values decrease quite rapidly. Since all temperature components are proportional to the shear rate, an intense decrease in temperature when the angle values corresponding to the plateau are exceeded indicates the formation of conditions for the gravity flow of the medium at lower mean integral values of the shear rates.

In accordance with the results of studies carried out in [6, 38], with an increase in the chute angle, the regime of developed fast shear flow is replaced by the regime of a splashing flow. Thus, the plateau of high temperature values corresponds to the range of chute angle values at which the transition from a developed fast shear flow to a splashing flow occurs. The transition is accompanied by a decrease in the average integral temperature of the granular medium due to a decrease in the shear component of the particle velocity in the flow volume. Refinement of the plateau area of high values of the temperature of a granular medium in a gravity flow on a rough chute is possible using the dependence of the total effect of its “heating” on the relative value of the slope angle. The corresponding dependence shown in Fig. 4 indicates that the region of maximum heating of the granular medium, which coincides with the region of transition from one flow regime to another, is located in the range of slope angles that satisfy the condition  $\sin\alpha/\sin\alpha_0 = 1.09 - 1.12$ .

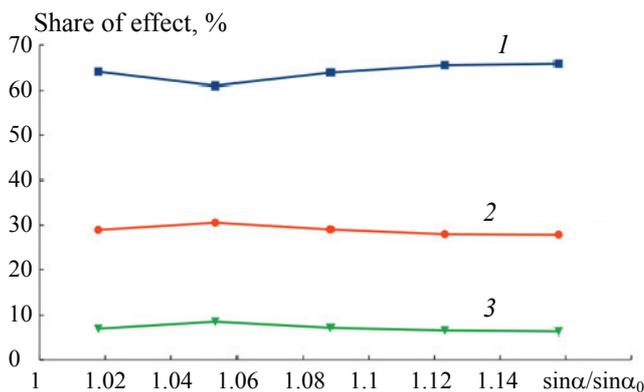
In order to assess the significance of the temperature components, Fig. 5 shows the dependences of their relative values on the chute angle. Relative values are defined as the ratio of the component to the sum of the values of all temperature components,



**Fig. 3. Mean integral values of the components of the temperature of the granular medium caused by shear movement (a), fluctuation (b) and transverse mass transfer (c) of particles in a fast gravity flow of glass beads, depending on the angle of inclination of a rough chute**



**Fig. 4. Mean integral value of the temperature of the granular medium in the fast gravity flow of glass beads, depending on the angle of inclination of the rough chute**

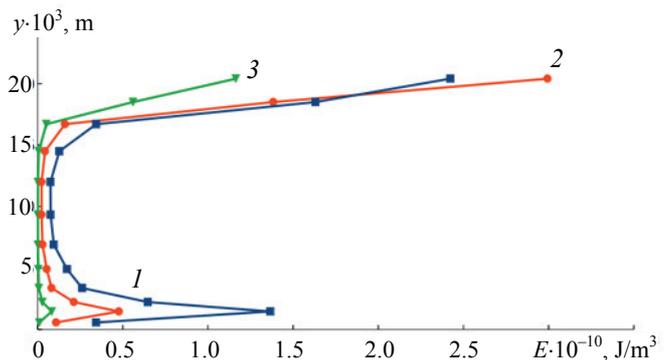


**Fig. 5.** To the assessment of the significance of quasi-thermal effects of the components of the temperature of a granular medium caused by shear movement (1), fluctuation (2), and transverse mass transfer (3) of particles in a fast gravity flow of glass beads, depending on the angle of inclination of a rough chute

expressed as a percentage. In accordance with the obtained dependences, the greatest quasi-thermal effect in the gravity flow of a granular medium falls on the shear component of the relative displacements of particles. An order of magnitude smaller quasi-thermal effect is characterized by the component of mutual displacements of particles, due to their transverse mass transfer. In the studied range of slope angles, the ratio of the values of the temperature components remains approximately at the same level.

However, it should be noted that what has been said refers to the mean integral temperature values in the material flow. As for the local values of the temperature components, their ratio changes significantly in particular zones along the layer height. In accordance with the results presented in Fig. 6, in the flow region adjacent to its open surface, the relative values of the temperature components increase due to fluctuations and transverse mass transfer of particles. In this case, the quasi-thermal effect caused by transverse mass transfer becomes comparable to the effect caused by the relative shear movement of particles. The observed features of quasi-thermal effects indicate the possibility of exerting a selective influence on the magnitudes of certain types of effects by corresponding changes in the structural and kinematic parameters of the flow.

Thus, the study of the temperature of a granular medium, as the kinetic energy of various forms of mutual displacements of particles under the conditions of a gravity flow on a rough chute, indicates its significant dependence on the chute angle. It was found



**Fig. 6.** Profiles of local values of the temperature components of the granular medium caused by shear displacement (a), fluctuations (b) and transverse mass transfer (c) of particles, in a fast gravity flow of glass beads at an angle of inclination of a rough chute  $\alpha = 28,5^\circ$

that at a slope angle  $\alpha$  corresponding to the condition  $\sin\alpha/\sin\alpha_0 = 1.09 - 1.12$  ( $\alpha_0$  is the angle of repose of the material), an extremely high mean integral temperature value is achieved. The specified range of chute angle values determines the region of transition from the developed shear flow regime to the splashing flow. The temperature components due to fluctuations, transverse mass transfer, and shear movement of particles are analyzed. It was found that in the investigated range of the chute angle at a constant flow rate, the ratio of the mean integral values of the temperature components remains approximately constant. The shear component of temperature makes the greatest contribution to the “heating” of the granular medium. The smallest quasi-thermal effect is characteristic of the temperature component due to transverse mass transfer, whose contribution to the “heating” of the medium is an order of magnitude less than that of the shear component.

It was found that the temperature profile (temperature change along the layer height) has a shape similar to the void fraction profile, which indicates a direct relationship between the structural and kinematic flow parameters. The ratio of local values of temperature components is variable and depends on a set of dynamic, structural and kinematic flow parameters. In the region of the flow adjacent to its open surface, the temperature component due to the transverse mass transfer of particles increases to a much greater extent than other components, and is aligned with them in order of magnitude.

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