unsteady conditions determined from quasisteady relations; p, pressure; r_0, pipe radius; q_w, heat flux density; $q = q_w r_0/\lambda t_{b0}$; Re, Reynolds number; Pr, Prandtl number; t, temperature; t_{b0}, inlet temperature; u_{max}, axial velocity; w, mean flow rate; x, longitudinal coordinate; $X = 4xu_{max}/dPrRew$; α, heat-transfer coefficient; β, volumetric coefficient of expansion; λ, thermal conductivity; τ, time. Indices: w, wall temperature; b, mean bulk temperature of stream.

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EXPERIMENTAL STUDY OF HYDRODYNAMIC AND HEAT-TRANSFER PROCESSES IN THE DOWNWARD MOTION OF A TWO-PHASE FLOW UNDER ANNULAR AND DISPERSED-ANNULAR CONDITIONS

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Relationships are derived for determining the average thickness of a liquid film and the predominant frequency of the wave motion on its surface under conditions of two-phase flow; relationships are also derived for calculating the hydraulic resistance and the rate of heat transfer to the film under these conditions.

A special characteristic of descending two-phase flows is the possibility of realizing an annular situation for any arbitrarily small rates of flow of the gas phase (in the limiting case, the free descent of the liquid). With increasing rate of gas flow, some of the liquid passes into the core of the flow, producing a dispersed-annular situation.

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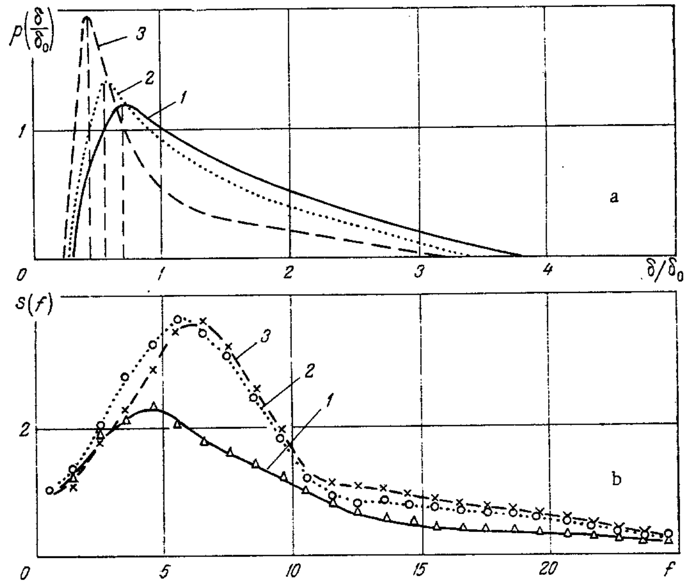


Fig. 1. Distribution density of instantaneous film thickness (a) and spectral density of the intensity of the process (b): Γ = 5.12 N/m·sec; L = 2.4 m; 1) G_g = 0.077 N/sec; 2) 0.0435; 3) 0.196; f, 1/sec.

The present investigation is devoted to an experimental determination of the local characteristics of a liquid film in the case of two-phase descending flows as well as the hydraulic resistance and heat transfer at various distances from the entry into the working section. The ranges of variation of the basic parameters were chosen in such a way as to be able to compare the results with those of other authors, for example, those relating to the hydraulic resistance and individual characteristics of a film [1,2] and so on.

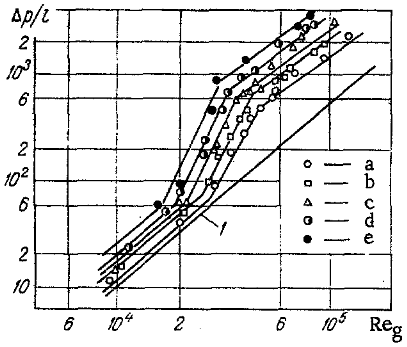
The investigations were carried out in working channels 3 m long; the working media were water and air at approximately atmospheric pressure.

The local characteristics of the liquid film were studied in an annular channel comprising an inner tube 61.2 mm in diameter made of steel 1Kh18N9T and a transparent outer Plexiglas shell making a gap 18 mm wide with the inner tube. The liquid flux density in the experiments varied over the range Γ = 1.37-16.2 N/m·sec, which at a temperature of 20-35°C corresponded to a range of film Reynolds numbers Re_δ = 120-1800. The rate of air flow at an air temperature of 15-25°C in the experiments varied from 0 to 8.8 N/sec; correspondingly, u_g = 0-20 m/sec, Re_g = 0-4.3·10^4.

The hydraulic resistances were studied in a working channel constituting a steel 1Kh18N9T tube with an internal diameter of 34 mm. The flux density of the liquid varied over the range 2.95 to 20.6 N/m·sec, so that at a temperature of 20-35°C, Re_δ = 400-2000. The gas flow rate was varied from 0 to 0.59 N/sec; correspondingly, u_g = 0-55 m/sec; Re_g = 0-120,000 (t_g = 20-30°C).

Investigations into the local heat-transfer coefficients were carried out in a working channel formed by a steel 1Kh18N9T tube with an internal diameter of 31 mm. The temperature of the liquid at the inlet varied over the range 30-45°C; the liquid flux density was 2.45-15.6 N/m·sec. The gas temperature at the inlet varied over the range 25-30°C, the gas flow rate was G_g = 0-0.264 N/sec, and, correspondingly, u_g = 0-30 m/sec. The channel was heated by means of pressurized hot water operating on a counterflow basis.

For measuring the local instantaneous thicknesses of the liquid film we used the earlier-devised capacity method [3], recording the results on a loop oscillograph. A special feature of the sensor employed in our investigations was the heating of a small movable condenser plate to a temperature of 130°C to prevent condensation and separation of liquid upon it. The experimental channels and measuring methods were described in more detail in [4,5]. Measurements were made in seven cross sections at distances of 0.2, 0.4, 0.6, 1.2, 1.6, 2.0, and 2.4 m from the inlet.



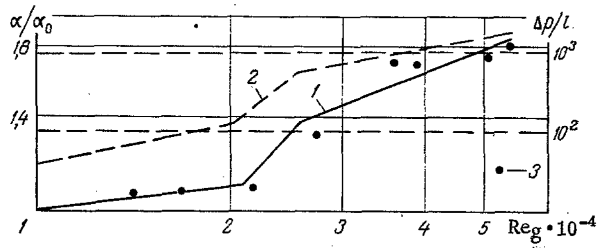


Fig.2

Fig.3

Fig. 2. Hydraulic resistance gradient as a function of the reduced Reynolds number of the gas; 1) resistance for the motion of air in a dry channel; L/d = const = 76.4; a) Γ = 2.95 N/m·sec; b) 5.12; c) 4.98; d) 15.5; e) 20.5 N/m·sec. $\Delta P/l$, N/m^2·m.

Fig. 3. Relative heat-transfer coefficient [1) determined from Eq. (18); 3) experimental] and hydraulic resistance gradient (2) as a function of the reduced Reynolds number of the gas. L = 2.55 m; Γ = 9.8 N/m·sec.

The hydraulic resistance was measured in three sections each 400 mm long, the upper cross sections of which lay at distances of 0.4, 1.2, and 2.4 m, respectively, from the entrance into the working channel. The resistance was determined from the fall in static pressures in the gas core or directly on the walls washed by the liquid.

The local heat-transfer coefficients were determined at distances of 0.75, 1.35, 1.95, and 2.55 m from the entrance into the working channel. The temperature of the wall surface and the average temperature of the film were measured in these sections with Chromel—Copel thermocouples. The distortion of the local temperature due to the fitting of the thermocouple into the wall of the tube was taken into account by calculation. The specific thermal flux was determined in a section 600 mm long by reference to the heat given out from the hot coolant and verified by reference to the heat passing into the flow, as indicated in the readings of special thermocouples.

A study of the local characteristics of the liquid film under the influence of the contiguous gas flow showed that in all cases studied wave motion developed on the surface. The character of the wave motion depends both on the rates of liquid and gas flow and on the path length. Up to a particular critical rate of gas flow (velocity) the average film thickness remains practically equal to the film thickness in a state of free fall. For gas flow rates greater than critical the average film thickness diminishes. In the cross sections a short way from the inlet of the working part the surface of the film becomes smooth; in those at greater distances from the inlet, in the majority of the experiments amplification of the surface wave perturbations takes place. In the cross sections at distances of 1.6–2.4 m from the inlet, for certain liquid flux densities the height of the waves increases with increasing rate of gas flow; subsequently it stabilizes and there is even a tendency for the effect to diminish.

The density of the distribution of instantaneous local thickness varies with the liquid flux density and the rate of gas flow, but a sharply expressed maximum appears for all the cases examined and in every cross section. The distribution of instantaneous thicknesses is asymmetrical. The range of variation of the thicknesses smaller than the most probable values is considerably narrower than the range of variation of those greater than the most probable.

Figure 1a shows the distribution densities of the average film thickness normalized with respect to its average thickness δ_0 in the case of free fall (Γ = 5.15 N/sec; L = 2.4 m). Figure 1b shows the distribution of the spectral intensity of the process for the same conditions. The maximum thicknesses increase with increasing gas flow. The thickness of the continuous layer changes very little. At the beginning of the working section (L = 0.2 m) no predominant (carrier) frequency can be distinguished either for the free fall of the liquid or for the case of an accompanying gas flow. The frequency distribution in the cross sections further down the flow (at L = 0.6–2.4 m) has a sharply expressed maximum in the range 3–8 1/sec (depending on the particular distance traveled), as indicated in Fig. 1b.

The critical gas flows (velocities) indicated above may be determined from the following expressions:

$$\frac{(u_g^\delta)^2_{cr}\,\gamma_g}{u_f^2\,\gamma_l} = 0.0776 \quad \text{for} \quad 200 \leqslant \mathrm{Re}_\delta \leqslant 300-400, \tag{1}$$

$$\frac{(u_g^\delta)^2_{cr}\,\gamma_g}{u_f^2\,\gamma_l} = 0.143 \quad \text{for} \quad \mathrm{Re}_\delta \geqslant 400-500. \tag{2}$$

For a gas flow rate greater than critical, the relative thickness of the film diminishes (within the range of liquid and gas flow rates studied and also within the limits of experimental accuracy) in proportion to the rate of gas flow. In the section of stabilized average thickness when

$$u_g^\delta\gamma_g > (u_g^\delta\gamma_g)_{cr} \quad \text{for} \quad \mathrm{Re}_\delta < 400,$$
$$\frac{\delta_{av}}{\delta_0} = 1 - 0.077\,\mathrm{Re}_\delta^{0.2}\left[\frac{u_g^\delta\gamma_g}{(u_g^\delta\gamma_g)_{cr}} - 1\right], \tag{3}$$

while for $\mathrm{Re}_\delta > 400$

$$\frac{\delta_{av}}{\delta_0} = 1 - 0.212\left[\frac{u_g^\delta\gamma_g}{(u_g^\delta\gamma_g)_{cr}} - 1\right]. \tag{4}$$

The section corresponding to the stabilization of the average film thickness was always less than 0.2 m for the laminar flow region, and in the turbulent-wave region less than 1.2 m.

The most probable carrier frequency of the wave motion on the film surface (for L > 0.6 m) may be determined from the relationship

$$\frac{f}{f_0} = 1 + (1 - 0.49\,\mathrm{Re}_\delta^{0.08}\left(\frac{u_g}{u_0} - 1\right), \tag{5}$$

where f_0 is calculated from the relationship given in [6]; $u_0 = 4$ m/sec is the characteristic rate of gas flow, beginning from which a change of carrier frequency occurred in each of the experiments. For $u_g < u_0$, $f/f_0 = 1$.

Our study of the hydraulic resistances showed that all three sections along the length of the channel were characterized by three kinds of dependence of the specific resistance $\Delta p/l$ on the rate of gas flow (Fig. 2).

At the boundary between the first and second regions there is an acceleration of the increment in resistance with increasing u_g, while at the boundary between the second and third regions the rate of increase in resistance diminishes. In all three characteristic regions the resistance is higher than in the dry channel and increases with rising density of the liquid flux density. The boundaries of the transition from one characteristic region of resistances to another are not constant, but depend on the liquid flux density, the distance of the experimental section from the inlet, and [by comparison with the results of other authors ([1,2,7],etc.)] the diameter of the working channel.

The first region corresponds to annular flow, with weak interaction of the phases. The boundary of this region corresponds to the prebreakaway conditions, for which the influence of the gas flow on the film characteristics is only beginning to make itself felt. In the first region it is convenient to discuss the resistance of the gas flow on the basis of the relative motion. The increase in the hydraulic resistance in the annular two-phase flow may be explained by the fact that, when the average relative velocity is equal to zero, the pulsation components may differ from zero, and hence the turbulent frictional stresses may assume a considerable value, so causing a rise in the effective frictional resistance.

An analysis of the quantities characteristic of the process (possibly of considerable importance in connection with the development of the finite pulsational velocity components), together with an analysis of our own experimental results and those presented in [1,2,7], enables us to describe the resistance coefficients in the first region by means of the equation

$$\lambda_I = \lambda_0\left[1 + 0.75\,(\mathrm{Re}_g^{rel})^{-0.51}\left(\frac{g\delta_0^3}{\nu_l^2}\right)^{0.505}\left(\frac{\sigma_l}{\gamma_l\,\delta_0^2}\right)^{0.08}\right]. \tag{6}$$

The second region is transitional. In this region a strong phase interaction starts appearing, leading to a considerable reduction in the average film thickness and to the smoothing (or, alternatively, the amplification) of the perturbations on the surface; the liquid starts breaking away from the crest of the wave, and the mode of flow transforms into the dispersed-annular variety.

The third region is the region of fully developed dispersed-annular flow. In this region we have the greatest increment in the resistance by comparison with that of the dry channel, and the difference between the various sections along the channel appears to the greatest degree. Owing to the difficulty of determining the actual flow characteristics, and most of all the true volumetric gas content, in order to generalize the experimental data in regions II and III it is convenient to use the "model of separate flows" by introducing a correction into the resistance coefficient of one (the gas) phase to allow for the effects of the other, The effective resistance coefficient should allow for the influence of all factors involved, including the pressure head, in view of the fact that it is impossible to determine the actual density of the mixture.

The reduced frictional resistance coefficients in the second and third regions are approximated by the equations

$$\lambda_{II} = \lambda_0 \left[1+2.95\cdot 10^{-20}\, \mathrm{Re}_g^{4.5} \left(\frac{L}{d}\right)^{0.812} \left(\frac{\nu_l^{2/3}}{g^{1/3} d}\right)^{5.5} \mathrm{Ga}^{1.6}\, \mathrm{Re}_\delta^{1.77}\right], \tag{7}$$

$$\lambda_{III} = \lambda_0 \left\{1 + 956\, \mathrm{Ga}^{-0.705}\, \mathrm{Re}_\delta^{0.75}\, \mathrm{We}^{-0.32} \left[1 + 533 \left(\frac{L}{d}\right)^{-2.5}\right]\right\}. \tag{8}$$

The boundary between regions I and II may be found from the critical value of the Reynolds number $\mathrm{Re}^{\mathrm{rel}}_{g\,\mathrm{cr}1}$

$$\mathrm{Re}^{\mathrm{rel}}_{g\,\mathrm{cr}1} = 186\, \mathrm{Re}_\delta^{-0.19} \left[\frac{d}{\left(\frac{\nu_g^2}{g}\right)^{1/3}}\right]^{0.642} \left[\frac{d}{\left(\frac{\nu_l^2}{g}\right)^{1/3}}\right]^{0.642} \left(\frac{L}{d}\right)^{-0.32}, \tag{9}$$

and the boundary between regions II and III from the critical value of the Reynolds number $\mathrm{Re}_{g\,\mathrm{cr}2}$:

$$\mathrm{Re}_{g\,\mathrm{cr}2} = 1150\, \mathrm{We}^{0.64} \cdot \mathrm{Re}_\delta^{0.096} \cdot \left(\frac{\nu_l}{\nu_g}\right)^{0.28} \left(\frac{L}{d}\right)^{0.09}. \tag{10}$$

Equations (6)-(10) serve to generalize and correlate our own experimental data with those of [1,2,7].

Before studying the local heat-transfer coefficients in the accompanying-flow case, we executed some control experiments on the free fall of the liquid film in the absence of an accompanying gas flow. The results indicated reasonable agreement with the computing relationship of [3] in a number of the experiments (for fairly low temperatures of the liquid at the inlet and high liquid flux densities).

The average local heat-transfer coefficient for the free fall of the liquid α_0 may be determined as the result of heat transfer over a certain time interval in which liquid layers of various thicknesses pass alternately through the section under consideration. The thickness of the liquid layer changes from the minimum to the maximum value; alternatively (subject to a certain averaging procedure) we may consider the limits of variation as extending from δ_{con} to δ_{pro} (from the average thickness of the continuous layer to the average height of the projections).

Let us assume that at every instant of time the velocity profile remains similar and corresponds to the equilibrium state in developed turbulent flow. Then at every instant of time the heat-transfer coefficient will be a function of the Re_δ number calculated in accordance with [3] from the instantaneous thickness of the layer of liquid. If

$$\mathrm{Re}_{\mathrm{weq}} = \frac{\mathrm{Re}_{\mathrm{pro}} + \mathrm{Re}_{\mathrm{con}}}{2} = \left(\frac{g}{0.0292\, \nu_l^2}\right)^{4/7} \frac{\delta_{\mathrm{pro}}^{12/7} + \delta_{\mathrm{con}}^{12/7}}{2}, \tag{11}$$

the equivalent "wave" thickness of the film will be

$$\delta_{\mathrm{weq}} = 0.308 \left(\frac{\nu_l^2}{g}\right)^{1/3} \mathrm{Re}_{\mathrm{weq}}^{7/12}. \tag{12}$$

We express the dimensionless heat-transfer coefficient — the Nusselt number — in the form

$$\mathrm{Nu}_{\mathrm{weq}} = \frac{\alpha_0 \delta_{\mathrm{weq}}}{\lambda}. \tag{13}$$

The experimental data regarding the heat transfer to the liquid film falling along the inner and outer surfaces of the vertical channels are approximated to a fair degree of accuracy by

$$Nu_{weq} = 0.4 \cdot 10^{-3}\, Re_{weq}^{1.15}\, Pr. \qquad (14)$$

The relationship for the local heat-transfer coefficient in the case of an accompanying gas flow (Fig. 3, curve 1) as a function of Re_g has the same character as the relationship $\Delta p/l = f(Re_g)$ (curve 2).

We may analyze the experimental local heat-transfer data corresponding to the action of an accompanying gas flow on the falling liquid film on the assumption that the principal thermal resistance is concentrated in the laminar sublayer close to the wall. According to an investigation carried out in the Moscow Higher Technical School [6], the dimensionless thickness of the laminar sublayer in the case of film flow remains approximately constant $\delta^{+}_{lam} = 5$.

Using the method of superposition, let us assume that the total tangential stress on the wall τ_0 is made up of the stress associated with free fall τ_{00} and an additional term $\tau_{\Delta p}$ associated with the reduction in static pressure which appears during the motion of the gas flow:

$$\tau_0 = \tau_{00} + \tau_{\Delta p}. \qquad (15)$$

The thickness of the laminar sublayer in the film for an accompanying gas flow will then be equal to

$$\delta_{lam} = \frac{5\nu_l\, \rho_l^{1/2}}{\sqrt{g\delta_0 + \tau_{\Delta p}}}. \qquad (16)$$

Let us consider that the temperature profile in the film remains in a similar configuration. Then for the case of the same thermal flux and the same liquid flux density the average temperatures in the cross section and the temperatures at the boundary of the laminar sublayer will also be the same. Let us further assume that the temperature only changes within the bounds of the laminar sublayer. We shall then have

$$\frac{\alpha}{\alpha_0} = \frac{\delta_{lam0}}{\delta_{lam}}. \qquad (17)$$

An analysis of the experimental data confirms the linear dependence of the function $\alpha/\alpha_0 = f(\delta_{lam0}/\delta_{lam})$. However, the real values of α/α_0 are higher than those calculated from Eq. (17), and this difference varies for different liquid flow densities, diminishing as Γ rises. The resultant experimental data may be excellently generalized by means of a single equation:

$$\frac{\alpha}{\alpha_0} = 1 = (1 + 2.88 \cdot 10^3 \delta_0^{*\,-1.72}) \left(\frac{\delta_{lam0}}{\delta_{lam}} - 1\right), \qquad (18)$$

where $\delta_0^* = \delta_0/(\nu_l^2/g)^{1/3}$ is the dimensionless film thickness for the case of free fall.

NOTATION

G_g, rate of gas flow, N/sec; Γ, gravimetric liquid flux density, N/m·sec; u_g, reduced gas velocity, m/sec; d, diameter of working channel (path length of accompanying flow), m; Re_g, reduced Reynolds number of the gas; u_g^δ, velocity of the gas in the constricted cross section of the channel, m/sec; u_g^{rel}, relative velocity of the gas, m/sec; Re_δ, Reynolds number of the film, $Re_\delta = \Gamma/\nu_l\gamma_l$; $\nu_{l,g}$, kinematic viscosity of the liquid and gas, m^2/sec; $\gamma_{l,g}$, specific gravity of the liquid and gas, N/m^3; u_f, average velocity of the liquid in the film, m/sec; δ, instantaneous thickness of the liquid film, m; δ_{av}, average thickness of the liquid film, m; δ_0, average thickness of the liquid film in the case of free fall, m; f, most probable "carrier" frequency of the wave process on the surface of the liquid film, 1/sec; f_0, most probable "carrier" frequency of the wave process on the surface of the liquid film in the case of free fall, 1/sec; $\Delta p/l$, hydraulic resistance gradient, N/m^2·m; $\lambda_{I,II,III}$, hydraulic resistance coefficient in regions I, II, and III of the hydraulic resistance characteristic; λ_0, coefficient of friction of the single-phase gas flow for a rate of flow G_g; We, modified Weber number for the two-phase flow, $We = u_g\gamma_g d/g\sigma_l$; σ_l, surface tension of the liquid, N/m; g, acceleration of free fall (gravity), m/sec^2; Ga, modified Galileo number for two-phase flow, $Ga = \sigma_l^{3/2}\, g/(\gamma_l - \gamma_g)^{3/2}\nu_l^2$; α_0, α, heat-transfer coefficients from the wall to the liquid film for the free fall of the latter and for the case of two-phase flow, W/m^2·°C; λ_l, thermal conductivity of the liquid, W/m·°C; Nu_{weq}, equivalent "wave" Nusselt number; Re_{weq}, equivalent "wave" Reynolds number; Pr, Prandtl number; τ, tangential stress at the wall, N/m^2; δ_{lam0}, δ_{lam}, thickness of laminar sublayer for the free fall of the film and in the two-phase flow, respectively, m; ρ, density of the liquid or gas, kg/m^3.

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DISPERSION OF THERMAL WAVES IN GRANULAR MATERIAL

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The effective thermophysical parameters of a dispersed medium are discussed which characterize the propagation of temperature waves in the medium and the equations of nonstationary thermal conductivity are formulated.

Many papers (see [1-5], for example, and the review in [6]) have been devoted to a detailed study of nonstationary fields of temperature or impurity concentration in dispersed or other heterogeneous media. The interest in this subject is connected with the commercial prevalence of periodically operating equipment in which such media are used as working bodies and also of equipment in which there is a "response" to a sudden change in external conditions (chromatographic columns, absorbers, etc.). Nonstationary transport processes play an important role in phenomena occurring within the individual porous grains of a catalyst [7, 8] or in particles being dried [9], which can also be considered as a kind of heterogeneous material. Finally, such processes are important in laboratory practice in the determination of effective dispersion coefficients for heat or mass in composite materials and in dispersed flows of diverse structure [10,11].

Even for an analysis of the penetration of heat in the simplest "composite" material — a system of two adjacent uniform blocks [12] — or from the consideration of heat propagation along identically oriented fibers of an ordered fibrous material [13], it is clear that the behavior of a nonstationary temperature field in heterogeneous and homogeneous media differs not only in quantitative and qualitative respects, but also depends strongly on the structural features of the medium. The latter is responsible for the significant spread in the experimental data obtained under various conditions even in materials of identical structure together with the lack of a common viewpoint on the mechanism for transport processes in heterogenous media [5-10], with attempts at deriving some correlation relations that would generalize such data leading to extremely diverse results depending on the type of computational model used for the generalization [11]. Therefore, an a priori formal simulation of these processes is clearly unsatisfactory, and one feels the need for development of more detailed physical representations in the formulation of a deeper theory based on them.

We consider below only granular materials, one phase of which consists of discrete particles distributed in the other phase. In the general case, both phases of the medium may be mobile but the Péclet number

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