ttp://www.moderntechno.de/index.php/meit/article/view/meit37-01-026
DOI: 10.30890/2567-5273.2025-37-01-026

UDC 504.453:551.48:556.5

FEATURES OF TRANSPORT PROCESSES IN TWO-PHASE CHANNEL FLOWS

ОСОБЛИВОСТІ ПРОЦЕСІВ ПЕРЕНОСУ В ДВОФАЗНИХ РУСЛОВИХ ПОТОКАХ

Hnativ I.R. / Гнатів І.Р.
PhD / доктор філософії
ORCID: 0000-0002-2987-1673
Ukrainian National Forestry University,
Lviv, Gen. Chyprynka Str., 134, Ukraine,79057
Національний лісотехнічний університет України,
м. Львів, вул. Генерала Чупринки, 134, Україна, 79057
Hnativ R.M. / Гнатів Р.М.
Doctor of Technical Sciences / Доктор технічних наук
ORCID: 0000-0002-4931-7493
Lviv Polytechnic National University, Lviv, Karpinsky str., 6, Ukraine, 79013
Національний університет «Львівська політехніка»,
м. Львів, вул. Карпінського, 6, Україна, 79013

Abstract. *One of the active methods of applying transport phenomena is the methods of transport of two-phase «suspension-carrying» flow. For such flows, the viscosity depends both on the shape of solid particles of the liquid medium and on their size. The presence of solid particles in dispersed flows also characterizes the concept of hydraulic size, which affects the velocity profile.*

Hydraulic size depends not only on the actual size of the particle, but also on its density, shape, surface condition, and also on the properties of the medium in which the particle moves. Two particles, regardless of their density, size, and other properties, are considered the same if, under standard conditions, they fall in water with the same velocities. During group fall of particles, the velocity of individual particles decreases and depends on the amount of looseness of the system (layer) of particles and their size.

This paper considers the features of transport processes in two-phase channel flows. The vertical component of the velocity of movement depending on the characteristics of the particles and their shape, as well as the main parameters of the particle shape, was generalized. The obtained formulas for effective viscosity are in quite satisfactory agreement with experimental data in the corresponding ranges of volume concentration changes. The mathematical apparatus of the theory of generalized functions can also be successfully used for rheological modeling of an arbitrary heterogeneous medium.

Keywords: *transport processes, hydraulic size, channel flows, particle characteristics, effective viscosity.*

Introduction.

One of the active methods of applying transport phenomena is the methods of transporting two-phase “suspended” flows. As is known, two-phase flows include dispersions of latexes and emulsions [1–4]. Latexes and emulsions are mostly non-Newtonian fluids, therefore their behavior and rheological state can be described by the corresponding equations of non-Newtonian fluids. Modeling of their behavior can be represented in accordance with the mechanical models of Rayner. Regarding dispersed and «suspension-carrying» flow, the viscosity depends both on the shape of solid particles of the liquid medium and on their size. For example, in two-phase flows, liquid-solid particles, the shape of which is spherical, and the size does not exceed 10 [5].

The main text

The viscosity of the mixture can be determined by Einstein's formula. In the case when solid particles have a shape other than a sphere (plate, prism, cube), the coefficient is corrected (Table 1). The presence of solid particles in dispersed flows also characterizes the concept of hydraulic size, which affects the velocity profile. Hydraulic size depends not only on the actual size of the particle, but also on its density, shape, surface condition, and also on the properties of the medium (usually water) in which the particle moves. Two particles, regardless of their density, size, and other properties, are considered identical if, under standard conditions, they fall in water with the same velocities. When particles fall in groups, the velocity of individual particles decreases and depends on the amount of looseness of the particle system (layer) and their size.

The hydraulic particle size of suspended solids is determined by conducting fractional or sedimentation analysis of the material and calculated according to the dependence [6]

$$U_0 = \frac{1000kh_1}{at\left(\frac{kh_1}{h}\right)^n} - \omega, \quad (1)$$

where k – building volume utilization factor; h_1 – depth of the working part of the structure, m; α – a coefficient that takes into account the effect of water temperature on its viscosity; t – settling time, s, corresponding to the specified effect of water purification from suspended solids and obtained under laboratory conditions in a water layer h = 500 мм; n – an indicator that depends on the agglomeration of suspended solids in the process of their deposition; ω — vertical component of the speed of water movement in the structure, mm/s.

Table 1. shows the dependences for calculating the vertical component of the velocity of movement depending on the characteristics of the particles and their shape.

Hydraulic size is used as one of the basic concepts in theories and working hypotheses of gravitational processes of mineral enrichment.

Table 1 - Vertical component of velocity depending on particle characteristics and their shape

№	Formula	Author	Particle characteristics, shape
1	$\omega = \frac{2gr^2(\rho T - \rho)}{9\mu}$	Stokes theoretical formula	Laminar flow at Re ≤ 1. For small particles, e.g., for silt particles
2	$\omega = \frac{25.8d\sqrt[3]{(\delta - 1)^2}}{9\mu}$	Allen	Turbulent flow. Large particles
3	$\omega = k\sqrt{d(\delta - 1)}$	Retinger	Resistance transition region. Medium-sized particles
4	$\omega = F\sqrt{dg\frac{(\rho T - \rho)}{\rho}}$	Ruby	Universal method. If the flow regime around the particles is not known, then the Ruby formula can be applied

The hydraulic size of soil particles is the speed of uniform fall of a certain heavy soil particle in a sufficiently large volume of water at rest. The speed depends on the size, geometric shape and density of the particle, as well as on the temperature of the water. The value of the speed is determined experimentally for various solid particles. For ice particles and air bubbles, the hydraulic size is a negative value.

In most cases, especially when analyzing movement in channels, the law of change of hydraulic size is described by a curve with a minimum in the upper part and a maximum in the lower part. Accordingly, the velocity diagram is an asymmetric curve, the maximum of which is located at points higher than the pipe axis. Therefore, in most cases for dispersed medium, the velocity distribution pattern has the form shown in Fig. 1.

For colloidal systems that move laminarly and have a dispersed phase in the form of spherical particles that have no intermolecular interaction, viscosity is described by Einstein's equation.

The results of comparing the calculated values of μ / μ_f with the experimental ones are shown in Fig. 2 [7]. The dots show the experimental values of μ / μ_f for the corresponding concentrations, and the solid lines 1, 2 and 3, 4 are the calculations according to the corresponding formulas (2-5).

$$\mu = \mu_f \left(1 + 2{,}5\overline{c}\right), \tag{2}$$

$$\mu = \mu_f \frac{1 + 0{,}5\overline{c}}{\left(1 - \overline{c}\right)^2}, \tag{3}$$

$$\mu = \mu_f \frac{1 + 1{,}5\overline{c}}{\left(1 - \overline{c}\right)^2}, \tag{4}$$

$$\mu = \mu_f \left(1 + 3{,}5\overline{c}\right). \tag{5}$$

The dotted line shows the calculation using the polynomial

$$\frac{\mu}{\mu_f} = 5{,}2335c^3 + 10{,}886c^2 + 2{,}6343c + 1{,}0336, \tag{6}$$

which approximates the experimental data and is obtained by the least squares method.

As we can see, the generalized formula (4) agrees quite well with the experimental data for moderate concentrations. $\overline{c} \le 0{,}3$. The root mean square deviations from polynomial (6) are: 0,1944 for experimental values and 0,011 for calculated curve 3. With further increase in concentration, the calculated values of relative viscosity μ / μ_f begin to deviate from the experimental ones. This is explained by the fact that at $\overline{c} > 0{,}3$ solid particles already noticeably affect each other, which is not taken into account by formula (4). Unlike (4), the simplified formula (5) is in quite satisfactory agreement with the experimental data in the concentration range $\overline{c} < 0{,}05$.

As for the classical formulas (2) and (3), according to the figure, they give somewhat underestimated calculated values.

The rheological method of determining the shape of particles is that diluted aggregate-stable disperse systems do not form structures and their rheological properties are close to or similar to the properties of the dispersion medium. The dependence of the viscosity of these systems on the concentration of the disperse phase is linear and is described by the Einstein's equation. Table 2 shows the main parameters of the shape of particles.

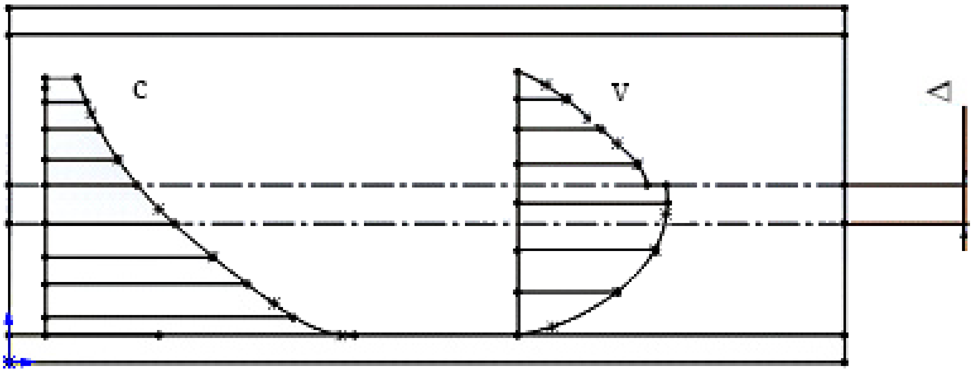

Fig. 1. Character of velocity distribution in a dispersed flow (c- concentration distribution)

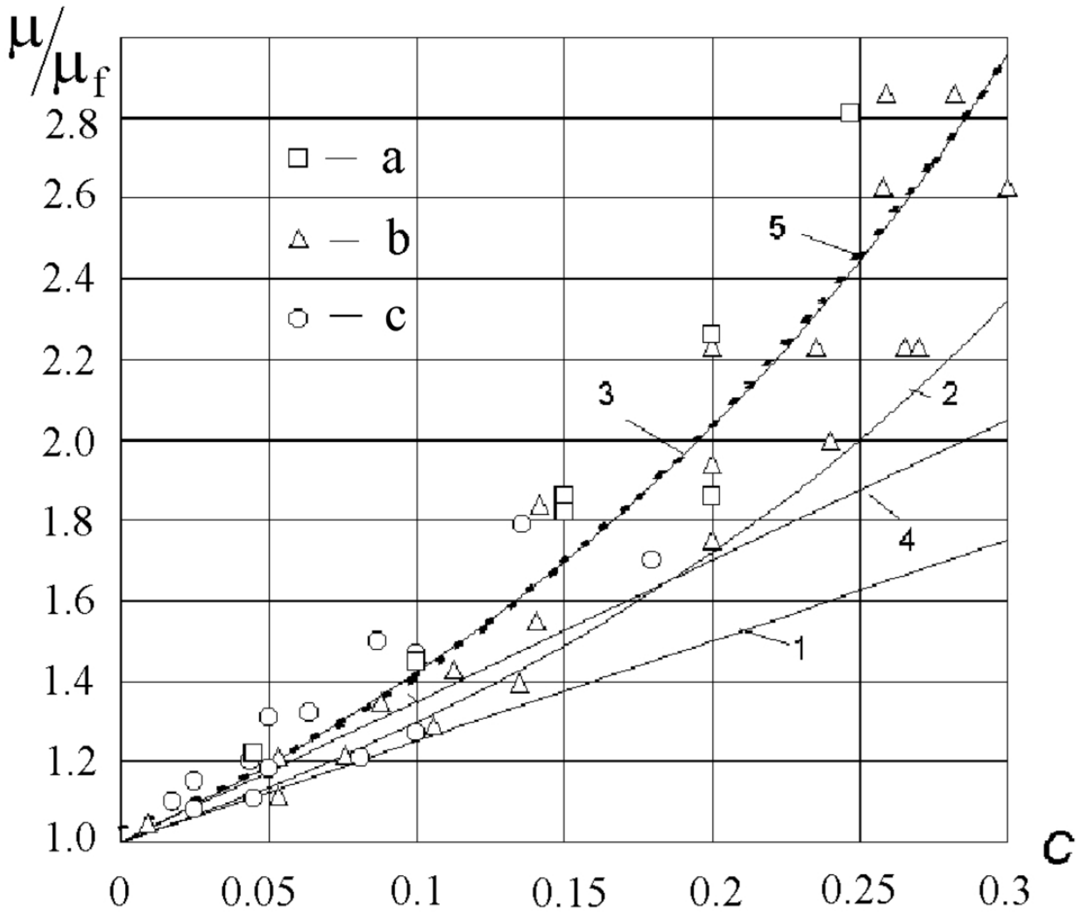

Fig. 2. Dependence of relative viscosity μ / μ_f on volume concentration c for suspensions of spherical solid particles [7]:

(research data borrowed from the works: a – *Happel J. and Brenner G*.**;**

b – *Thomas D.G.;* **c –** *Kobernik S.G. and Voitenko V.P.***)**

1 - 5 - *calculation using the appropriate formulas* **(2), (3), (4), (5), (6)**

Table 2 - Main parameters of particle shape [3]

Particle characteristics	Particle shape				
Description of a geometric figure	Sphere 	Cube 	Prism 	Fiber 	Plate 
Size ratio *a:b:c*	a=1 b=1 c=1	a=1 b=1 c=1	a=1 b=1 c=1,5-4,0	a=1 b=1 c>10	a=1 b=10-25 c=10-25
Coefficient *k* $S_{уд}=S_o/V=k/a$	6	6	4	4	2
Viscosity coefficient *a* $\eta=\eta_0(1+a\varphi_\Phi)$	3,5	4	3-6	3-6	-5
Examples of fillers	Boron nitride, silica gel	Calcinite, feldspar	Silicon oxide, barium oxide	Asbestos, basalt, boron, carbon fibers	Kaolin, talc, mica, graphite

The dependences $\eta=f(\varphi\Phi)$ determine the value of the coefficient and draw a conclusion about the shape of the particles (Fig. 3) [2, 4, 8].

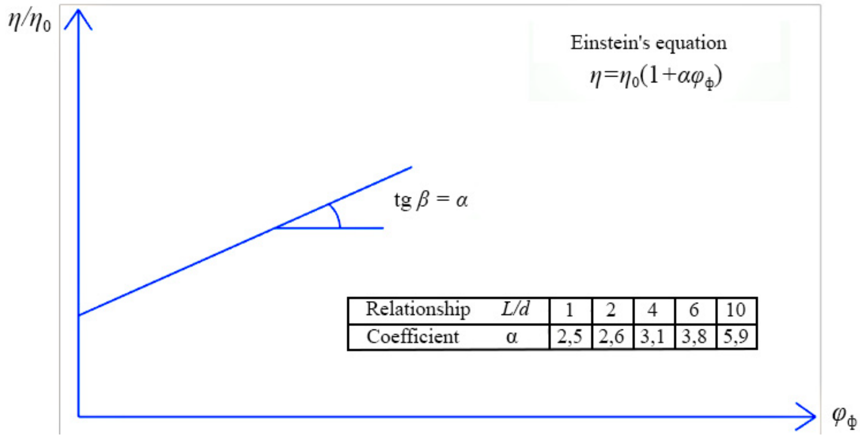

Fig. 3. Before determining the particle shape of Einstein's viscosity equation

For specific surface area, adsorption and kinetic methods are used. Adsorption methods are based on determining the volume or mass of a substance adsorbed on the surface and forming a monomolecular layer. Gases, liquids, and solids are used as adsorbates. The most widespread are the gas adsorption method and the method of adsorption of surfactants from solutions.

Kinetic methods are based on measuring the resistance to filtration of air or gases through a layer of powder. Filtration is carried out at atmospheric pressure or under vacuum.

Conclusion and findings.

This paper considers the features of transport processes in two-phase channel flows. The vertical component of the velocity of movement depending on the characteristics of the particles and their shape, as well as the main parameters of the particle shape, was generalized. The obtained formulas for the effective viscosity are in quite satisfactory agreement with the experimental data in the corresponding ranges of changes in the volume concentration. The mathematical apparatus of the theory of generalized functions can also be successfully used for rheological modeling of an arbitrary heterogeneous medium.

References:

1. Anderson Dale, Tannehill John C., Pletcher Richard H. (2016). Computational Fluid Mechanics and Heat Transfer (Series in Computational and Physical Processes in Mechanics and Thermal Sciences) 3th Edition. Taylor & Francis, 774p.

2. Башта Т. М. Машиностроительная гидравлика: справочное пособие. М.: Машиностроение, 1971. 320 с.

3. Яхно О.М., Ночніченко І.В., Гнатів Р.М., Гнатів І.Р. (2023). Явища переносу в екологічних середовищах. Львів: Видавництво Львівської політехніки, 2023. 316 с. https://vlp.com.ua/node/20797

4. Бирхгоф Г. М. Гидродинамика. М.: Иностр. литер., 1963.244 с.

5. Білецький В. С. (2004). Мала гірнича енциклопедія: у 3 т. Д.: Донбас, Т. 1. 640 с.

6. Beek W. J., Muttzall K. M. K., Van Heuven J. W. (1999). Transport Phenomena, 2nd Edition ed. by John Wiley & Sons, Inc. 344 p. https://www.wiley.com/en-be/Transport+Phenomena%2C+2nd+Edition-p-9780471999904

7. Кріль С.І. (2003). До питання про реологічне моделювання суспензій. Прикладна гідромеханіка. Том 5 (77), №2. С. 20-26.

8. Strutinskiy V., Yakhno O., Machuga O., Hnativ I., Hnativ R. (2018). Analysis of interaction between a configurable stone and a water flow. Eastern-European Journal

of Enterprise Technologies. Vol 6, No 10 (96): Ecology. P. 14-20. https://doi.org/10.15587/1729-4061.2018.148077

Анотація. *Одним з активних методів застосування явищ переносу є методи переносу двофазних «завислонесучих» потоків. Для дисперсних та «завислонесучих» потоків в’язкість залежить як від форми твердих часток рідинного середовища, так і від їхніх розмірів.*

В’язкість суміші можна визначати за формулою Ейнштейна. Наявність твердих частинок у дисперсних потоках характеризує також поняття гідравлічної крупності, яка впливає на профіль швидкості. Гідравлічна крупність залежить не тільки від реальних розмірів частинки, але й від її густини, форми, стану поверхні, а також від властивостей середовища (зазвичай – води), в якій відбувається рух частинки. Дві частинки, незалежно від їх густини, крупності і інших властивостей, вважають однаковими, якщо за стандартних умов вони падають у воді з однаковими швидкостями. За групового падіння частинок швидкість окремих часток зменшується і залежить від величини розпушеності системи (шару) частинки і їх крупності.

У більшості випадків, особливо при аналізі руху в каналах, закон зміни гідравлічної крупності описується кривою з мінімумом у верхній та максимум в нижній частині. Відповідно епюра швидкостей є асиметричною кривою, максимум якої знаходиться в точках вище від осі труби.

У даній роботі розглянуто особливості процесів переносу в двофазних руслових потоках. Було узагальнено вертикальну складову швидкості руху в залежності від характеристик частинок та їх форми, а також основні параметри форми частинок. Одержані формули ефективної в’язкості цілком задовільно узгоджуються з експериментальними даними у відповідних діапазонах зміни об’ємної концентрації. Математичний апарат теорії узагальнених функцій може бути успішно використаний також для реологічного моделювання довільного гетерогенного середовища.

Ключові слова: *процеси переносу, гідравлічна крупність, руслові потоки, характеристики частинок, ефективна в’язкість.*

Стаття відправлена: 16.02.2025 р.