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A Model of the Dependence of the Settling Velocity of Water Droplets on the Turbulent Diffusion Coefficient in Oil

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Abstract. Oil emulsions are used in the extraction and refining operations of oil. The physical characteristics and structure of the oil emulsion are greatly altered by the presence of dissolved paraffin, mineral salts, dis-tributed water, and solid phase particles. Oil emulsion separation is typically done in two steps. Initially, there is a rapid surface deposition of big droplets followed by coalescence. By creating an intermediary layer inside the device, very tiny drops stay in the form of "fog" and are deposited for an extended period. The productivity of the extraction process is often determined by the rate of stratification. It is best to think of the emulsion that results from mixing oil with reservoir water as a mechanical combination of two insoluble liquids (oil and water). Currently, one of the liquids is dispersed throughout the volume of the other in the form of various-sized drops. The cost of transportation goes up because of the water content in the oil, which also causes the transported liquid's volume and viscosity to increase. Equipment used in oil transportation and oil refining experiences wear and tear due to water solutions containing mineral salts. In oil refineries, the presence of even 0.1% water in the oil results in severe foaming of the oil in the rectification cylinders, violating the processing regime and contaminating the condensation devices.

Keywords: oil droplets; turbulent diffusion coefficient; turbulent flow; coalescence, deformation of drops.

Introduction

To keep it apart from mechanical mixtures, oil that has been released from gases is held in specific containers for a predetermined amount of time [Kel17, Kel18, Sha18, Ras25]. These combinations separate from the oil when they sink to the bottom of the tanks. At this point, the majority of the water in the crude oil starts to naturally separate. Nevertheless, a certain proportion of tiny, difficult-to-separate water droplets are frequently present in oil. It might be challenging to separate water and oil when they are in an emulsion. The oil still contains tiny particles of suspended water. We have examined the impact of these droplets' turbulent diffusion coefficient on oil deposition in this work [Li21, Lia21, Sun20].

In actuality, different structures and fillings added to precipitators are utilized, and centrifugal forces are employed to enhance phase separation. Occasionally, stratification is also made possible by the high-voltage direct current's internal electric field [Sil21]. The density and size of the droplets, which follow the dynamic equilibrium conditions and guarantee the continuation of precipitation, as well as the main flow's velocity, define the structure of the pulsing interlayer [Lia21, Pat10, Pal17, Lei22].

The intermediate layer that forms in precipitation devices is subject to many structural changes, such as compression, expansion, stratification based on height and size, densification, and movement. With its characteristics, it is comparable to the "hot layer" of drops. To explain the droplets' mobility, let us assume the following circumstances [Rid21]:

a) drops are only spherical and this is determined by the small value of the Weber number:

$$W_e \ll 1;\ W_e=\rho_m U^2 a/\sigma_m;$$

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b) the washing of drops in the intermediate layer has a viscous character and is obtained from the condition of a small value of the Reynolds number:

$$Re_d = \frac{\Delta U a}{\nu_m} < 1, \qquad \left(\Delta U = \left|U - V_p\right|\right). \tag{1}$$

Here U is flow rate, V_p is velocity of drops in turbulent flow, a is the size of the drop, ν_m is kinematic viscosity of the medium.

c) there are no electrostatic, thermo- and diffusiophoretic and non-hydrodynamic effects in the flow. Droplet transfer by efficient diffusion and deposition is an exception. In this case, deposition effects for Stokes drops

$$\tau_r = \frac{1}{18}\frac{\rho_d a^2}{\eta_m}$$

or large size drops

$$\tau_r = \frac{\rho_d a^2}{18\eta_c\left(1 + Re_d^{2/3}/6\right)}$$

is expressed. Here, ρ_d is the density of the drops, η_m is the dynamic viscosity of the medium, τ_r is the relaxation time of the drop, and the size of the drop [Man21].

It should be noted that the turbulent diffusion coefficient plays an important role in the processes of droplet coalescence and destruction in isotropic turbulent flow, and its value is determined according to (2) for the range of different values of the turbulent pulsation scale λ.

$$\lambda > \lambda_0, D_T = \alpha_0(\varepsilon_R \lambda)^{1/3}\lambda; \;\; \lambda < \lambda_0, D_T = \alpha_0(\varepsilon_R \lambda)^{1/2}\lambda^2. \tag{2}$$

1. The Turbulent Diffusion Coefficient of Droplets

The complexity and intensity of suspended particle movement in a turbulent liquid flow vary in all directions as compared to laminar flows. Small-sized particles will travel along intricate trajectories in fluids and will be fully engaged in turbulent pulsations in scattered systems. The turbulent pulsation of the particles will diminish as a result of the particles getting bigger and falling behind the fluid's flow. It should be noted that the precipitation speed of the particles as well as the flow speed will determine the turbulent diffusion coefficient for large particles in a turbulent flow. The following formula can be used to determine the turbulent diffusion coefficient of particles during the turbulent flow of dispersed systems 0.

$D_{TR} \approx \mu^2 D_T$, where D_{TR} is the turbulent diffusion coefficient of particles, D_T is the turbulent diffusion coefficient of the liquid, μ^2 is the degree of attraction of particles by the pulsating medium, which depends on the size of the particles. In a broader sense, empirical formulas were proposed for determining the diffusion coefficients of particles depending on the dynamic speed of the flow, settling speed, etc.

$$\mu^2 = \frac{1}{1 + \omega^2 \tau_R^2}. \tag{3}$$

Here ω – turbulent pulsation frequency, τ_R – is the relaxation time of the particles. The value of μ varies between $0 \leq \mu \leq 1$. For small-sized particles, the value of μ is zero, and for large-sized particles, μ approaches unity.

Regarding the strength of the finely divided particles' attraction:

$$\mu = \frac{1}{\left[1 + \left(\frac{\rho_d a^2 \omega}{18\eta_c}\right)\right]^{1/2}}. \tag{4}$$

2. Findings and Conversation

A number of empirical dependences for vertical and horizontal channels can be determined utilizing different experimental research, e.g., to estimate the turbulent diffusion coefficient in turbulent flow:

$$D_{TR}/D_T = \mu^2 = 0{,}023\Psi\,(U_D)\left(\frac{U_D^2}{V_S}\right)^{1/4}; \tag{5}$$

$$Re_d = \frac{V_S a}{\nu} \le 5.$$

Here V_S is droplet settling velocity, $\Psi\,(U_D) = 1 + 0{,}786 \times 10^{-6} U_D^4$, $U_D = \frac{0{,}2U_s}{Re^{1/8}}$ – dynamic flow rate, U_s is the mean velocity of the turbulent flow. If $Re_d > 5$, then we get the following expression:

$$D_{TR}/D_T = \mu^2 = 0{,}054\left(\frac{U_D^3}{V_S}\right)^{1/4}. \tag{6}$$

Outcomes and conversation. Many empirical dependences on vertical and horizontal channels can be established utilizing different experimental research, e.g., to determine the turbulent diffusion coefficient in turbulent flow (Table 1).

Table 1

Displays the particles turbulent diffusion coefficient during liquid flow in a vertical channel

U_s, m/sec	U_d, cm/sec	a, mcm	V_S, cm/sec	D_T, cm²/sec	D_{TR}, cm²/sec	μ^2	Re_d
1,55	9,0	80	17	6,3	0,370	0,059	< 5
3,44	18,0	80	17	12,6	1,35	0,107	< 5
7,60	36,0	80	17	25,2	10,1	0,386	< 5
1,55	9,0	150	50	6,3	0,26	0,045	= 5
3,44	18,0	150	50	12,6	1,05	0,082	= 5
7,60	36,0	150	50	25,2	6,20	0,295	= 5
1,55	9,0	200	69	6,3	0,20	0,032	> 5
3,44	18,0	200	69	12,6	0,44	0,038	> 5
7,60	36,0	200	69	25,2	1,22	0,046	> 5

The following adjustments for the turbulent diffusion coefficient for horizontal ducts were derived from experimental data showing the motion of solid particles and oil droplets in the air flow.

$$\frac{D_{TR}}{D_T} = \mu^2 = 0{,}24\left(\frac{V_s}{U_D^3}\right)^{1/4}, \qquad Re_d \ge 2{,}5; \tag{7}$$

$$\frac{D_{TR}}{D_T} = \mu^2 = k(V_S)\left(\frac{V_S}{U_D}\right)^{1/4}, \qquad Re_d < 2{,}5. \tag{8}$$

Here $k(V_S)$ is a parameter whose value is

$$k(V_S) = \frac{2{,}16}{V_S^{1/8}}.$$

The expression shows that the turbulent diffusion coefficient in horizontal channels is directly proportional to the settling velocity and inversely proportional to the dynamic velocity, in contrast to vertical channels. As a result, the settling velocity determines the diffusion coefficient for both horizontal and vertical channels, and this dependence grows with increasing particle size. The impact of particle mass on the diffusion coefficient is demonstrated by the relationship between the turbulent diffusion coefficient of particles and the precipitation rate. If an increase in particle mass in vertical channels mostly results in the particle falling behind the main medium's speed, then an increase in particle mass in horizontal channels will directly impact the particle's diffusion coefficient. The computation and experimental values of the turbulent diffusion coefficient in horizontal channels are compared in the following Table 2.

Table 2

Experimental evidence and calculated values of the turbulent diffusion coefficient of solid particles
(in air a = 100–200 mm, Re_d > 2.5 in a square channel with a cross section of 76×76 mm 0

U_s, m/sec	U_D, cm/sec	V_S, cm/sec	D_T, cm²/sec	D_{TR}, cm²/sec	μ^2
7,6	40,7	41	23,5	0,9	0,038
16,7	81,0	41	63,7	1,5	0,023
25,9	119,0	41	103,0	1,8	0,017
7,6	40,7	104	23,5	1,36	0,048

The following dependence was found between the estimated values of the turbulent diffusion coefficient and the experimental indicators, based on the indicators listed in Table 2.

Larger colloidal particles are present in the flow despite dispersed systems (emulsions, suspensions) being characterized by polydispersity of particles, the sizes of which primarily fluctuate in the broad range of 1–200 μm. The minimum and maximum particle sizes generally represent the condition of dispersed flow, which controls the structure of the dispersion spectrum, its aggregative resistance to size change, and its precipitation resistance to precipitation. It is important to highlight that the processes that take place in dispersed systems are not only accompanied by collisions and the expansion of colliding drops, but also by the opposite phenomenon known as fragmentation. Fragmentation refers to the division of particles in a mixed effect or the capacity to maintain a continuous state, as well as the external or spontaneous disintegration of particles under any kind of impact on the surface. Thus, in dispersed systems, there is such a size of the drop, amax, that the drop is unstable, deformed and quickly disintegrated at sizes higher than this; and the minimum amino size indicates the lowest droplet durability limit, or rather, drops that have reached this size under certain flow conditions cannot be crushed any more. The maximum size of the particles characterizes the discontinuity of the droplets, and this dispersed environment depends on the hydrodynamic conditions of the flow, so that the turbulent flow is accompanied by a tendency to break up and break up individual drops under certain conditions.

CONCLUSION

In order to describe the movement of solid particles and oil droplets in vertical and horizontal channels, expressions for the turbulent diffusion coefficient are provided based on experimental observations. The formulas show that the turbulent diffusion coefficient in horizontal channels is directly proportional to the settling velocity and inversely proportional to the dynamic velocity, in contrast to vertical channels. As a result, the settling velocity determines the diffusion coefficient for both horizontal and vertical channels, and this dependence grows with increasing particle size.

The impact of particle mass on the diffusion coefficient is demonstrated by the relationship between the turbulent diffusion coefficient of particles and the precipitation rate. If an increase in particle mass in vertical channels mostly results in the particle falling behind the main medium's speed, then an increase in particle mass in horizontal channels will directly impact the particle's diffusion coefficient.

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Название: Модель зависимости скорости осаждения капель воды от коэффициента турбулентной диффузии в нефти.

Аннотация: Масляные эмульсии используются в операциях по добыче и переработке нефти. Физические характеристики и структура масляной эмульсии сильно изменяются из-за присутствия растворенного парафина, минеральных солей, дисфильтруемой воды и твердофазных частиц. Отделение масляной эмульсии обычно выполняется в два этапа. Первоначально происходит быстрое поверхностное осаждение крупных капель с последующим коалесцентным слиянием. Создавая промежуточный слой внутри устройства, мельчайшие капли остаются в виде «тумана» и откладываются в течение длительного периода. Продуктивность процесса экстракции часто определяется скоростью стратификации. Эмульсию, возникающую в результате смешивания масла с пластовой водой, лучше всего рассматривать как механическую комбинацию двух нерастворимых жидкостей (масла и воды). В настоящее время одна из жидкостей рассеивается по всему объему другой в виде капель различного размера. Стоимость транспортировки возрастает из-за содержания воды в масле, что также приводит к увеличению объема и вязкости перевозимой жидкости. Оборудование, используемое при транспортировке и переработке нефти, изнашивается из-за водных растворов, содержащих минеральные соли. На нефтеперерабатывающих заводах наличие в масле даже 0,1% воды приводит к сильному вспениванию масла в цилиндрах ректификации, нарушению режима обработки и загрязнению конденсационных аппаратов.

Ключевые слова: капли масла; коэффициент турбулентной диффузии; турбулентное течение; соединение и деформация капель.

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