Theory of breakup of pesticide drops in turbulent flow during plant spraying

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Quality of breakup of drops of pesticide solutions during crop spraying is of more critical importance compared to other factors, as it may considerably mitigate technogenic impact on the environment and, in general, contributes to significant reduction in use of the respective preparations without compromising the quality of technological process. The article analyses theoretical studies on breakup of drops of pesticide solutions in turbulent flow of two-phase media and presents a possible solution of analytical problem at various parameter values of pesticide solutions and turbulent air flow with consideration of mass transfer between small and large drops. Moreover, possible evaporation and condensation of solution drops are also taken into account. The resulting analytic dependencies allow describing the process of breakup of liquid by gas during crop spraying and determining the equivalent diameter of pesticide drops.

Breakup of drops, pesticide, environment, crop spraying

Introduction

Quality of breakup of drops of pesticide solutions during crop spraying is of more critical importance compared to other factors, as it may considerably mitigate technogenic impact on the environment and, in general, contributes to significant reduction in use of the respective preparations without compromising the quality of technological process. Theoretical analysis of interaction between a viscous drop of a pesticide and air (gas) flow is one of the most complex tasks of continuum mechanics. Its complexity originates in usually unstable non-stationary process of flow and in disturbances that cause disintegration of drops, consequently leading to broken axial symmetry of flow, which makes Navier-Stokes non-linear system of equations difficult to apply at the respective boundary and initial conditions.

Theoretical background

The phenomena of deformation and breakup of drops in gas flow have been studied by many scientists, such as (Hinze, 1948), (Gordon, 1959), (Dodd, 1960), (Simons, 1976), (Li & Fogler, 1978), (Borodin et. al., 1962), (Volynskii & Lipatov, 1970), (Gonor & Zolotova, 1981), (Levich, 1959) and others.

J.O. Hinze was one of the first to suggest taking Weber number as the criterion of stability of drops. He also showed that the type of deformation of disintegrating drops depended on the type of flow (uniform, accelerated, rotational).

It must be noted that J.O. Hinze analysed drop breakup on the basis of hydrodynamic theory developed by G.I. Taylor and A.N. Kolmogorov. In contrast to the theory by Kolmogorov-Hinze, (Sleicher, 1962) noted that viscous forces as well as the degree of effect of flow velocity must be taken into account. In this respect, work by (Rosenzveig, 1981) is particular interest as it has suggested the dependence for the most stable size of a drop.

Rayleigh-Taylor analysis of instability at flow acceleration has been analysed by (Harper et. al., 1972). They have determined dependence of breakup time on Weber number at high velocities of continuous medium relative to movement of a drop.

Breakup of a drop of a given diameter starts at specific, i.e. critical $V_{кр}$ (m/s), velocity of continuous medium flow. In case of liquids of low viscosity, where the process of breakup virtually does not depend on viscosity, critical velocity is determined by the following dependence:

$$V_{кр} = \kappa \left(\frac{\sigma}{\rho_1 d_o} \right)^{\frac{1}{2}}, \qquad (1)$$

where κ is the index of instability of drops. According to experimental data (Volynskii & Lipatov, 1970), κ ranges from 10.7 to 14.0.

Building on the assumption that transverse pressure gradient may be replaced with its average value. W.G. Reineke and G.D. Waldman (1970) established the equation of transverse deformation of a drop.

Calculation results have been supported by experiments using X-rays to measure mass loss as a result of disintegration of a drop (Reineke & Waldman, 1970).

In paper (Borodin et. al., 1962) conditions of static equilibrium of a drop under aerodynamic resistance and surface tension force were analysed.

Theoretical findings on breakup of drops presented above have limited applicability, as they have been derived from approximate account of only some of the factors defining the analysed phenomenon. Hence, much attention has been given to empirical study of the processes of deformation and breakup of drops. In this respect, papers (Reineke & Waldman, 1970; Gelfand et al. 1971; Ivandajev et. al., 1981; Ranger, 1972) are worth noting.

Issues of pesticide reduction in plant spraying and environmental protection have been in particular focus recently in various countries worldwide (Kapustin & Biriukova, 2008; Steponavičius et. al., 2009; Crooks et. al., 2001; Attané et. al., 2007; Forster et. al., 2012). It is further important to theoretically analyse the breakup of pesticide drops in turbulent flow of two-phase media and present a possible solution of analytical problem at various parameter values of pesticide solutions and turbulent air flow with consideration of mass transfer between small and large drops.

Aim of the paper. To analytically examine the process of breakup of pesticide drops in turbulent flow.

Results and discussion

W.G. Reineke and G.D. Waldman (1970) have provided evidence for five characteristic types of breakup of drops (Fig. 1). Based on the analysis of theoretical and empirical studies, it is possible to define characteristics of the specified types of breakup of drops.

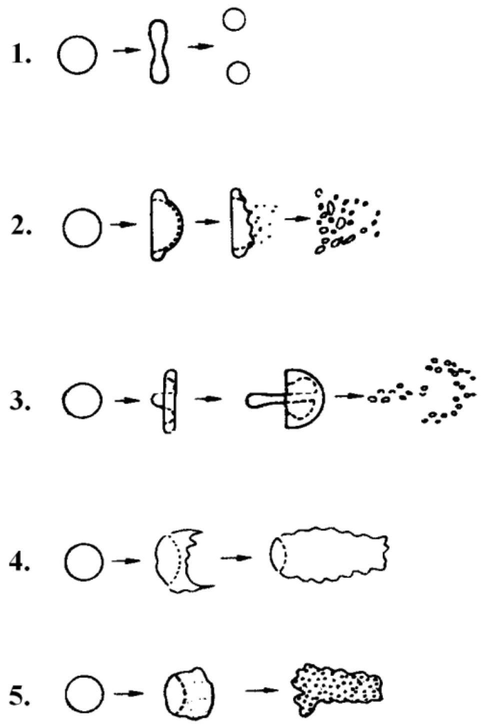

Fig 1. Main types of breakup of drops in air (gas) flow:
1 – vibrational breakup; 2 – bag breakup; 3 – bag-and-stamen breakup; 4 – sheet stripping; 5 – explosive breakup

The first type of breakup (vibrational breakup) is characterised by decomposition of an initial drop into two or a few smaller drops of approximately the same size. This type of breakup occurs at sudden impact by gas flow and low values of Weber number (dimensionless value, $W_e \approx 10$).

The second type of breakup (bag breakup) occurs at value of numbers W_e equal to approximately 20. The drop initially takes off and becomes the shape of a lens. It gradually inflates in the centre with subsequent breakdown into multiple tiny splashes.

The second type – bag-and-stamen – occurs at values of number ($W_e \approx 70$). In this case, mass of the drop concentrates on the periphery of the bag in the form of wet vapour. The bag bursts first, then wet vapour breaks up, and the column disintegrates into drops.

The following type of breakup – sheet stripping – occurs as a result of continuous stripping of surface layer of a drop. As the drop reaches a certain critical size, it disintegrates into tiny particles. Characteristic value of Weber number for this type of breakup: $W_e \approx 1000$.

Explosive type of drop breakup is observed at large values of Weber number ($W_e \approx 50000$). When the drop becomes subject to strong and sudden flow, it almost immediately disintegrates into multiple tiny drops.

Empirical studies refer to the case, where air flow suddenly impacts on the flow of drops. Main impact of air flow on drops has been little studied. Meanwhile, such conditions usually develop at atomization of pesticides during crop spraying. It must be noted that currently available theoretical and empirical data do not allow describing with sufficient accuracy or providing specific recommendations on solution of the problem of interaction between drops and gas flow. Additional empirical studies are necessary in each specific case by comparing own results with data obtained by other authors.

The problem of non-stationary mass exchange in gas-liquid system at translational movement of dispersion phase is solved for an individual drop (Uspenskii & Sharapov, 1974). In reality, there is mass exchange with a group of drops, which brings essential changes to interaction between phases of the flow. In this case, merging of tiny drops with other tiny and larger drops, as well as breakup of large drops should be taken into account. The processes of evaporation of drops or their condensation may also take place.

Analytical description of the process of breakup of liquid by gas and determination of equivalent diameter of drops is the following (Uspenskii & Sharapov, 1974):

$$\frac{\partial \Phi_i}{\partial \tau} - \frac{3}{2} \cdot P_e \cdot \frac{A\cos\Theta\zeta_1}{(1-B\chi^{1,5})M(\Theta)V_c} \cdot \frac{\partial \Phi_i}{\partial \zeta_i} + \frac{3}{4} \cdot P_e \cdot \frac{A\sin\Theta}{(1-B\chi^{1,5})M(\Theta)V_c} \cdot \frac{\partial \Phi_i}{\partial \Theta} = \frac{\partial^2 \Phi_i}{\partial \zeta_i}, \qquad (2)$$

where $i = 1$ (continuous medium); $i = 2$ (dispersion medium);

$$\Phi_i = \frac{C_i - C_\infty}{C_o - \alpha C_\infty}; \quad P_e = \frac{2V_c R}{D_i};$$

$$V_c = \frac{Q_2}{F_o}; \quad \tau = \frac{D_1 t}{R^2};$$

$$\zeta_1 = \frac{y}{R}; \quad \zeta_2 = \frac{y}{R}\beta_1;$$

$$y = r - R; \quad y \prec\prec R;$$

$$R = \frac{d}{2}; \quad \beta_1 = \left(\frac{D_1}{D_2}\right)^{\frac{1}{2}};$$

α – distribution coefficient dependent on the temperature; d – equivalent diameter of the drop (m); R – radius of the drop (m); D – diffusion coefficient (m^2/s); Q_2 – flow rate of dispersion phase (m^3/s); F_o – original section of passage (m^2); r and Θ – radial and polar coordinates of spherical coordinate system, related to the centre of a drop, respectively (m) and (rad.); y – radial coordinate of coordinate system related to the wall of passage (m); t – time (s); C_i – concentration of substance (kg/m^3); C_o and C_∞ – original concentration and concentration at a remote distance (kg/m^3); χ – specific atomization (kg/m^2).

In equation (7), B and $M(\Theta)$ are determined by the following equations:

$$B = 597\left(\frac{\mu_2}{\sqrt{\sigma_2\gamma_2}}\right)^{0,45}, \qquad (3)$$

$$M(\Theta) = 2\left(1+\frac{1}{3}\varepsilon^2+\frac{1}{8}\varepsilon^4+\frac{1}{87}\varepsilon^6\right)\sin\Theta -$$

$$-6\left(\frac{1}{145}\varepsilon^4+\frac{1}{135}\varepsilon^6\right)\sin 3\Theta + 10\left(\frac{2}{945}\varepsilon^6\right)\sin 5\Theta.$$

μ_2 – coefficient of dynamic viscosity of liquid (kg/m·s); σ_2 – liquid surface tension force (N); γ_2 – specific weight of liquid (N/m^2);

$$\varepsilon = \frac{\pi}{10\sqrt[3]{\frac{\pi}{6\chi}}-1}.$$

Equation (3) may be reduced to the following:

$$\frac{\partial\Phi_i}{\partial x} = \frac{\partial^2\Phi_i}{\partial\eta_i^2}; \quad i=1, \eta_1>0 \quad and \quad i=2, \eta_2<0, \qquad (4)$$

where $\eta_1 = \frac{1}{2}(P_e)^{\frac{1}{2}}\sin^2\Theta$.

Boundary conditions and conjugating conditions are written as follows:

$$\Phi_1(\eta_1;0)=0; \quad \Phi_1(\infty;x)=0; \quad \Phi_2(\eta_2;0)=1;$$
$$\Phi_2(-\infty;x)=1; \quad \alpha\Phi_1(0;x)=\Phi_2(0;x) \qquad (5)$$

$$\beta\frac{\partial\Phi_i}{\partial\eta}(0;x) = \frac{\partial\Phi_2}{\partial\eta_2}(0;x).$$

Solution of equation (3) at boundary conditions (5) is the following (Karslou & Eger, 1964):

$$\Phi_1 = \frac{1}{\alpha+\beta}erfc\frac{\eta_1}{2\sqrt{x}}; \quad \eta_1 \geq 0; \qquad (6)$$

$$\Phi_2 = 1-\frac{1}{\alpha+\beta}erfc\frac{|\eta_1|}{2\sqrt{x}}; \quad \eta_2 \leq 0. \qquad (7)$$

Having changed to physical values, the equations are as follows:

$$\frac{C_1-C_\infty}{C_o-\alpha C_\infty} = \frac{1}{\alpha+\beta}erfc\left[\frac{(P_e)^{\frac{1}{2}}}{4}\cdot\frac{\sin^2\Theta}{\chi^{\frac{1}{2}}}\cdot\frac{y}{R}\right]; \qquad (8)$$

$$\frac{y}{R}>0;$$

$$\frac{C_2-\alpha C_\infty}{C_o-\alpha C_\infty} = 1-\frac{1}{\alpha+\beta}erfc\left[\frac{(P_e)^{\frac{1}{2}}}{4}\cdot\beta^{\frac{1}{2}}\cdot\frac{\sin^2\Theta}{\chi^{\frac{1}{2}}}\cdot\frac{|y|}{R}\right]; \qquad (9)$$

$$\frac{y}{R}<0.$$

Similar dependencies can be obtained in the case of heat exchange between drops and gas.

It should be emphasized that at group movement of drops, mass exchange depends not only on P_e criterion, but also on physical parameters of the liquid. However, this dependence is difficult to identify when processes are examined with reference to one drop.

Conclusion

Analytic dependencies that allow describing the process of breakup of liquid by gas during crop spraying and determining the equivalent diameter of pesticide drops by air (gas) and identifying equivalent diameter of pesticide drops in crop spraying have been identified.

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Теория дробления капель ядохимикатов в турбулентном потоке при опрыскивании растений

Резюме

При опрыскивании сельскохозяйственных культур наиболее важное значение уделяется качеству дробления капель растворов ядохимикатов, которое существенно снижает техногенную нагрузку на окружающую среду и, в целом, способствует значительному снижению расхода препаратов без снижения качества технологического процесса. В статье приводится анализ теоретических исследований дробления капель растворов ядохимикатов в турбулентном патоке двухфазных сред и показана возможность решения указанной аналитической задачи при различных значениях параметров растворов ядохимикатов и турбулентного патока воздуха с учетом массообмена мелких и крупных капель. При этом учитывается возможность испарения капель растворов и их конденсация. Полученные аналитические зависимости дают возможность описать процесс дробления жидкости газом и установить эквивалентный диаметр капель ядохимикатов при опрыскивании сельскохозяйственных культур.

Дробление капель, ядохимикаты, окружающая среда, опрыскивание с.х. культур

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