CHEMICAL ENGINEERING TRANSACTIONS
VOL. 80, 2020
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Eliseo Maria Ranzi, Rubens Maciel Filho

ISBN 978-88-95608-78-5; **ISSN** 2283-9216
DOI: 10.3303/CET2080020

Size Distribution of Drops in A Regular-Packed Scrubber

Marat Z. Yeskendirov*, Alexander A. Volnenko, Zhakhongir Ye. Khussanov, Marina M. Yeskendirova, Gamidulla E. Tileuov

M. Auezov South Kazakhstan State University, Kazakhstan, Shymkent, Tauke Khan Avenue, 5
yesmm1203@gmail.com

The equation for the calculation of a mean size of liquid drops and a kind of a dimensional distribution function of the drops formed at a liquid dispersion in a regular-packed scrubber have been suggested in the present article. The proposed technique is based on the maximum entropy principle (MEP) with use of a dissipative approach. It was established that the distribution of drops according to their sizes in a regular-packed scrubber is described by the Rosin-Rambler equation. The influence of a turbulent gas flow's energy on a liquid's dispersion process is taken into consideration by application of the Kolmogorov-Obukhov law. The article contains the comparison of the calculation and experimental results. Despite the application of a number of simplifications at the modelling the experimental data have shown a satisfactory correspondence to the calculated results. The results obtained can be useful at engineering design of chemical apparatuses.

1. Introduction

Mass transfer processes in gas-liquid systems are often carried out at intensive regimes of fully developed turbulence at high gas rates (Bird, et al., 2007). Such regime is realised in apparatuses with a regular packing (Volnenko, et al., 2015) at the expense of introduction of discretely distributed or movable solid bodies in a contact zone. This regime promotes the growth of turbulent diffusion of the components (Shakirova, et al., 2014) and development of a drop surface of the phase contact (Serikuli, et al., 2014).

A liquid phase in the packing volume is as a film on the packing elements and as drops in the space between the elements. Owing to high rates of a gas stream that is accelerated at flow over the packing elements the film is sprayed; it leads to formation of a large quantity of fine drops of various sizes. Dispersion of the formed liquid drops depends on the gas-liquid interaction regimes and design parameters of the packing.

Prediction of the drops' dispersion and size distribution is of great importance for the fundamental analysis (Maćkowiak J., 2018) and practical calculations (Flagiello, et al., 2018) of heat and mass transfer processes in apparatuses with a drop structure of a gas-liquid interaction.

Classical models for prediction of the drops' diameters and rates distribution in turbulent gas flows were obtained on the basis of experimental data. In this case the distribution curves are constructed on the basis of the experiments carried out at various regime and design parameters. Such the approach is a foundation for Rosin-Rambler, Nukiyama-Tanasawa, log-normal and other distributions (Ashgriz, 2011).

The basic problem of empirical distributions is a fact that they are applicable for a certain narrow set of experimental data and are not suitable for description of the distributions with a wide change limit of drops' sizes (Paloposki, 1994).

On the basis of the statistical approaches based on the maximum entropy principle (MEP) it is possible to obtain a more general view of the drops' size distribution (Babinsky, et al., 2002). The MEP approach allows us to predict the most probable drops' size distributions taking into account the accessible information about the liquid dispersion mechanism (Movahednejad, et al., 2010).

The purpose of the given work was to obtain a kind of the drops' size distribution function on the basis of the MEP approach taking into consideration the turbulent mechanism of liquid dispersion in a regular-packed scrubber.

Paper Received: 30 October 2019; Revised: 25 January 2020; Accepted: 20 April 2020
Please cite this article as: Yeskendirov M., Volnenko A., Khussanov Z., Yeskendirova M., Tileuov G., 2020, Size Distribution of Drops in a Regular-packed Scrubber, Chemical Engineering Transactions, 80, 115-120 DOI:10.3303/CET2080020

2. Governing Equations

Formation of the drop stream in a regular packed bed occurs after disintegration of the film and jet streams at the expense of the disturbances caused by influence of turbulent pulsations of the medium (Serikuli, et al., 2014). Dispersion of the liquid is accompanied by formation of quite coarse drops with a diameter of D_c that is proportional, according to Rayleigh (Kolev, 2011), to the disturbance wave length. Conceding that a volume of the formed coarse drop is equal to a volume of the initial (undisturbed) part of the jet which length is equal to the disturbance wave length, it is possible to obtain a formula for calculation of the coarse drops' diameter:

$D_c = 1{,}89 B_j d_{jm}$, (1)

where B_j - an experimental coefficient depending on the hydrodynamic regime of gas-liquid interaction in the packing bed; d_{jm} - the jet mean diameter.

The coarse drops formed at the jet disintegration are unstable in the turbulent gas flow and have the ability to secondary dispersion and formation of an ensemble of the drops with smaller diameter of D_m ; these drops are steady (equilibrium) in the gas flow with the given dynamic pressure.

On the basis of solution of a balance equation of the forces operating on a unit drop and using the dissipative approach (Shakirova, et al., 2014) the following formula for determination of the mean drop diameter has been obtained:

$$D_m = A\left(\frac{\sigma^{3/5} d_{jm}^{2/5}}{\psi_p{}^{2/5} \rho_g^{2/5} \rho_l^{1/5} u_g^{6/5}}\right) \qquad (2)$$

here A - an experimental coefficient depending on a type of the packing element, σ - a surface tension coefficient, ψ_p - a resistance coefficient of the packing element, ρ_g - the gas density, ρ_l - the liquid density, u_g - the gas rate.

The intensive turbulence of the continuous flow in a regular-packed bed, which structure is close to a homogeneous structure, predetermines the equiprobable existence of the pulsation spectrum in the scale of $l \pm \Delta l$ responsible for formation of the drops in the size of $D \pm \Delta D$ in all the flow volume under the stipulation that $l \sim D$.

The dispersion process is a relaxation one, then the dispersed phase can be represented as the closed macro system with generalized coordinates generally equal to spatial coordinates (pulsation rates, sizes, impulses etc.) of all the drops.

Using basic provisions of equilibrium statistical physics for a closed macro system, for which a set of possible states is discrete, it can be written (Shannon, et al., 1949):

$$\sum p_i \varepsilon_i = \overline{G} \,, \qquad (3)$$

$$\sum p_i = 1 \,. \qquad (4)$$

Here p_i – detection probability of a closed macro system in i state; ε_i – energy of a macro system in i state; $\overline{G}$ – the average value of dispersed phase's total energy.

Entropy of the micro system under discussion, characterized by a discrete set of its possible states, is:

$$S\left(\{p_i\}\right) = -\sum p_i \ln p_i \qquad (5)$$

According to the maximum entropy principle in case of the equilibrium distribution of $\{p_i\}$ not only the fulfillment of conditions (3) and (4) takes place but also the entropy value is maximized.

Some researchers (Van der Geld, et al., 1994) stated that the Shannon entropy is not a relevant criterion if to use a drop volume instead of a drop diameter. This fact was considered in the paper (Cousin, et al., 1996). The authors specified that the MEP should be used for prognostication of the size distribution if it is known that the drops are spherical. They suggested new adequate approaches to the choice of the restrictions based on some representative diameters of the obtained distribution:

$$\int_0^\infty f(\varepsilon)\, d(\varepsilon) = 0 \qquad (6)$$

$$\int_0^\infty f(\varepsilon)\,\varepsilon^q \cdot d(\varepsilon) = (\bar{\varepsilon})^q \, . \qquad (7)$$

Here q is an order of a restriction; it is analogous to the distribution parameter in the Rosin-Rambler formula, $(\bar{\varepsilon})^q$ - representative energy of a drop. It produces:

$$f_0 = \exp\left(-\lambda_0 - \lambda_1 (\bar{\varepsilon})^q\right), \qquad (8)$$

where λ_0, λ_1 – Lagrangian arbitrary multipliers.

Thus, the equilibrium probability distribution of the closed macro system is determined in accordance with equation (8) as the most probable distribution from all the distributions satisfying conditions (6) and (7).

Being based on formula (8) it is possible to calculate the energy distribution probability of an individual drop:

$$f(\varepsilon) = \frac{1}{\varepsilon}\exp\left(-\frac{\varepsilon}{\bar{\varepsilon}}\right). \qquad (9)$$

Assuming that the drops are in the thermodynamic and hydrodynamic equilibrium with the gas surrounding them and have a spherical form, it is possible to connect the energy with the drops' sizes and pass to the size distribution function. For this purpose let us represent the drop energy as a sum of its internal ε_v and surface ε_s energies:

$$\varepsilon = \varepsilon_v + \varepsilon_s = \frac{\pi}{12}\rho_l \left(\overline{u'}\right)^2 D^3 + \pi\sigma D^2 \, , \qquad (10)$$

The average value of the pulsation rate can be determined on the basis of the Kolmogorov-Obukhov law (Kolmogorov A.N., 1991):

$$\overline{u'} = BE^{1/3} l^{1/3} \, , \qquad (11)$$

here l - a scale of the vortexes (pulsations) effectively influencing on the coarse drops, E - dissipation energy, B - a special coefficient.

The dissipation of energy in the liquid mass is determined as a ratio of the power of the vortex P_v formed at flow of the packing element to the liquid mass m_l (Hanna, et al., 1982):

$$E = \frac{P_v}{m_l} \, , \qquad (12)$$

The vortex power and the mass in this formula are calculated by the following way:

$$P_v = \psi_p S_p \frac{\rho_g u_g^3}{2} \qquad (13)$$

$$m_l = V_l \rho_l \, , \qquad (14)$$

where ψ_p - a resistance coefficient of the packing element, S_p - cross-section area of the packing element, V_l - the liquid volume on the packing element.

The energy distribution function $f(\varepsilon)$ and the drops' size distribution function $f(D)$ are connected by the following relation:

$$f(D) = f(\varepsilon)\frac{d\varepsilon}{d(D)} \, . \qquad (15)$$

Solving equation (15) in view of (9) – (14) gives the following expression:

$$\mathrm{f}(D)=\frac{3D^2\left(1+\frac{2}{3}\frac{\beta}{We}\right)}{\overline{D^3}\left(1+\frac{\beta}{We}\right)}\exp\left[-\frac{D^3\left(1+\frac{\beta}{We}\right)}{\overline{D^3}\left(1+\frac{\beta}{We}\right)}\right], \qquad (16)$$

where $\beta=\frac{14{,}3}{\psi^{2/3}}\left(\frac{\rho_g}{\rho_l}\right)^{1/3}$, We - the Weber number.

For the cases when $\rho_l >> \rho_g$ expression (16) can be represented as:

$$f\left(D_d\right)=\left(\frac{2{,}73}{D_m}\right)^3 D^2\exp\left[-0{,}32\left(\frac{D}{D_m}\right)^3\right]. \qquad (17)$$

Here D_m - the mean equilibrium drop diameter.

Equations (16) and (17) are analogous to the Rosin-Rambler equation but they were obtained on the basis of the MEP approach taking into consideration the turbulent mechanism of liquid dispersion in a regular-packed apparatus.

The test of equations (16-17) was implemented at the experimental setup represented in Figure 1.

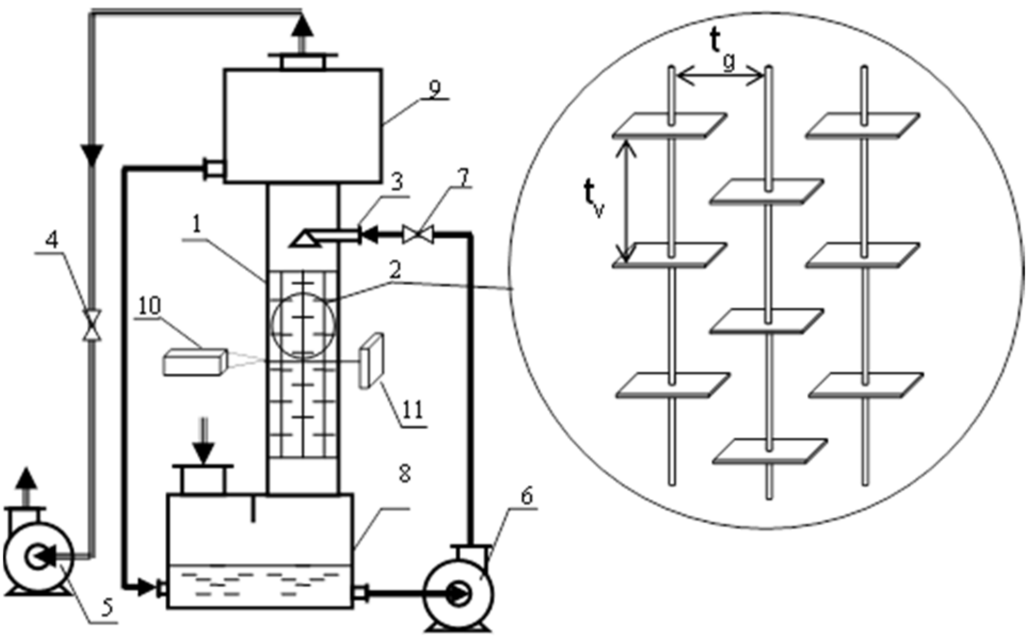

Figure 1: Schematic diagram of the experimental setup
1 – a column; 2 – a packing; 3 – a liquid distributor; 4 – a gate valve; 5 – a fan; 6 – a pump; 7 – a valve; 8 – a circulating (discharge) tank; 9 – a drop catcher; 10 – a laser with telescopic expanders and a cylindrical lens; 11 – a camera.

Regular packing 2 was located in glass square-section column 1 with the side of 450 mm. The packing elements producing the turbulence represented square metal plates with a side of $b = 0.1\ (m)$ placed on a thin metal core with a vertical step of $t_V = 2b$. The plates on the next cores were fixed in the staggered order. The step between the cores was $t_g = b$.

The experimental setup works in the following way. An air flow due to the vacuum induced by fan 5 is fed in a vertical working channel of glass column 1. Water for spraying is fed in the column through distributor 3. The air and water discharge rates are regulated by way of gate valve 4 and valve 7. The installation operates according to a counterflow regime of phase interaction.

During the experiment the gas (air) rate in the free column area changed in limits of $u_g = 1 \div 6\ (m/s)$, the specific mass discharge of water was in interval of $L = 5 \div 20\ (kg/m^2s)$. The dispersion of drops was measured by the Doppler laser anemometric technique (Albrecht, et al., 2003).

The essence of the method consists that the flow under consideration at full absence of any external lighting is illuminated with the narrow laser radiation beam produced in the demanded direction by means of laser 10 with telescopic expanders and a cylindrical lens. In the process the flow under study is cut by the light plane that provides visualisation of any particles or, generally, any interphase boundaries passing through this plane owing to refraction and dispersion of the laser radiation on these interphase boundaries. Registration of the observed picture is made by means of camera 11.

Some experimental results (the step line) and the calculated distribution curve (the solid line) are represented in Figure 2.

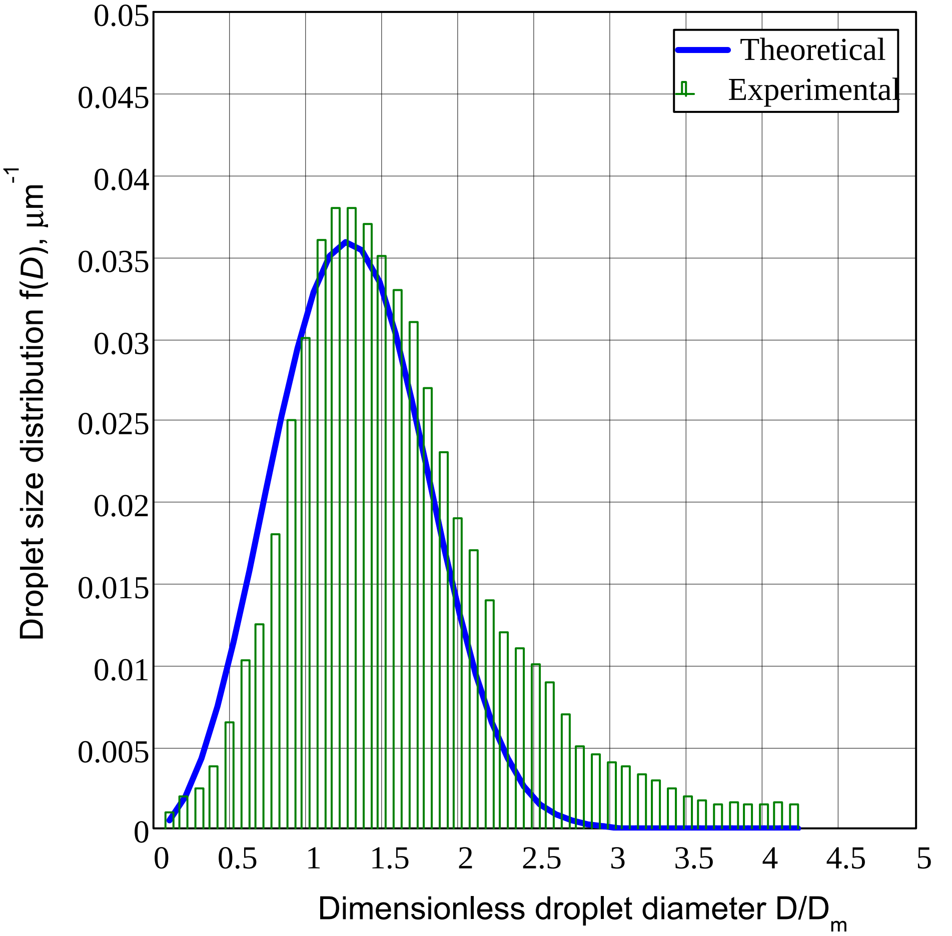

Figure 2: Comparison of theoretical (solid line) and experimental (step line) drop size distribution.

Gas rate $u_g = 4\ (m/s)$; *specific mass water discharge* $L = 12\ (kg/m^2s)$;

horizontal and vertical steps – 2b

As follows from the figure, in the area of fine and average drops there is the satisfactory correspondence between the theoretical and experimental results. In the field of coarse drops there is the insignificant disagreement of the results.

3. Conclusion

The kind of the size distribution function of the drops in a regular-packed scrubber was determined in the work using the maximum entropy principle. For taking into account of the turbulence effect on the liquid's dispersion process the dissipative approach was used.

It was established that the distribution of drops in accordance with their sizes in a regular-packed scrubber is determined by the Rosin-Rambler equation. However, in this work the empirical coefficients characteristic for the Rosin-Rambler equation were determined analytically on the basis of consideration of the liquid dispersion mechanism in a regular-packed bed.
In spite of the application of some simplifications at the modelling the experiment data showed the satisfactory conformity to the calculation results.
The above permits us to draw a conclusion that the application of the MEP for prediction of the drops' size distribution in a regular packed bed has shown the most adequate identification satisfying to laws of conservation of mass, momentum and energy. The results obtained can be useful for calculation of intensity of mass transfer processes in chemical apparatuses and for optimum designing purposes.

References

Albrecht H.E., Borys M., Damaschke N. and Tropea C., 2003. Laser Doppler and Phase Doppler Measurement Techniques, Springer-Verlag.

Ashgriz N., 2011. Handbook of Atomization and Sprays. Springer New York Dordrecht Heidelberg London.

Babinsky, E. and Sojka, P.E., 2002. Modeling droplet size distributions. Prog.Energ.Combust. Sci., 28, 303-329.

Bird R.B., Stewart W.E. and Lightfoot E.N., 2007. Transport phenomena. John Wiley & Sons.

Cousin J., Yoon S.J., Dumouchel C., 1996. Coupling of Classical Linear Theory and Maximum Entropy Formalism for Prediction of Drop Size Distribution in Sprays. Application to Pressure-Swirl Atomizers, Atomization Sprays 6, 601–622.

Flagiello D., Di Natale F., Carotenuto C., Erto A., Lancia A., 2018. Seawater desulphurization of simulated flue gas in spray and packed columns: an experimental and modelling comparison, Chemical Engineering Transactions, 69, 799-804 DOI: 10.3303/CET1869134.

Hanna S., Hess W. and Klein R., 1982. Self-diffusion of spherical Brownian particles with yard-core interaction. Physica, 111A, 181-199.

Kolev N.I., 2011. Multiphase Flow Dynamics 2. Springer-Verlag Berlin Heidelberg.

Kolmogorov A.N., 1991. Dissipation of energy in the locally isotropic turbulence. Proc. Math. Phys. Sci., 434(1890), 15-17. [http://www.ams.jhu.edu/~eyink/Turbulence/ classics/Kolmogorov41c.pdf].

Mackowiak J., 2018, Random packing modeling under high pressure for gas-liquid systems, Chemical Engineering Transactions, 69, 793-798 DOI: 10.3303/CET 1869133.

Movahednejad E., Ommi F.S. and Hosseinalipour M., 2010. Prediction of Droplet Size and Velocity Distribution in Droplet Formation Region of Liquid Spray. Entropy, 12, 1484-1498.

Paloposki T., 1994. Drop Size Distributions in Liquid Sprays. ActaPolytechnicaScandinavica, Mech. Eng. Series 114, Helsinki, Finland.

Shakirova A., Eskendirov M., Syrmanova K., Shakirov B., 2014, Dissipative approach to the calculation of the diffusion coefficient of the aerosol in turbulent flows, Chemical Engineering Transactions, 39, 1213-1218 DOI:10.3303/CET1439203.

Shannon C.E. and Weaver W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana, IL, USA.

Serikuli Z., Volnenko A.A. and Kenig E.Y., 2014. Hydrodynamic of Apparatuses with Preformed Packing Bodies. Procedia Technology, 12, 375-381.

Van der Geld C. W. M. and Vermeer H., 1994. Prediction of Drop Size Distributions in Sprays Using the Maximum Entropy Formalism: The Effect of Satellite Formation. Int. J. Multiphase Flow 20 (2), 363–381.

Volnenko A.A., Balabekov O.S., Korganbaev B.N. and Sarsenbekuly D.S., 2015. Purification Apparatuses with New Types of Regular Packings for Chromium Salts Production. Chemical Engineering Transactions, 43, 1147-1152 DOI: 10.3303/CET1543192.