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EVALUATING GEOMETRIC PARAMETERS OF DISPERSED PARTICLE AGGREGATES

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ВИЗНАЧЕННЯ ГЕОМЕТРИЧНИХ ХАРАКТЕРИСТИК АГРЕГОВАНИХ УТВОРЕНЬ ДИСПЕРСНИХ ЧАСТИНОК

The particle size largely determines the properties of dispersed materials. It is a key parameter for equipment performance evaluation. The measurement process is substantially complicated by the presence of aggregated structures.

Purpose. To develop complex method for evaluating geometrics of emulsion drops and other dispersed formations of spherical particles considering their aggregation. The method is based on aggregate structure and contours, using marking of analyzed objects.

Methodology. The method includes several steps: image filtering, converting it to a monochrome mode, evaluating the aggregate contour, correcting the contour, setting particle markers according to glares on particle surfaces, making the skeleton, determinating connecting points. To decompose aggregate fragments containing several markers, aggregate's area is distributed between the particles according to the Voronoi diagram. Parameters of circles corresponding to particles are evaluated from geometrics of corresponding aggregate fragments. The method is illustrated by the images of real emulsion fragments (type II emulsions – water in oil).

Findings. The developed method allows realizing segmentation of complex structured aggregates, consisting of many spherical particles, containing internal objects whose contour is located entirely inside the aggregate. The number of incoming particles is not limited.

Originality. The developed method of aggregate segmentation (emulsion drops) is noise-resistant and allows segmenting the aggregates of a complex structure by evaluation of connecting points of its particles, according to the aggregate structure and by marking the particles when evaluation of connecting points with the necessary precision is impossible (in case of a small convexity defect or presence of internal particles). The glares on particle surfaces may serve as markers.

Practical value. The method may be used to evaluate dispersity of emulsions and other finely divided materials at various industries.

Keywords: *aggregate, dispersive structures, segmentation, Voronoi diagram, markers, particle connecting points*

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Introduction. The finely divided materials are used in different branches of activity: in the energy sector, metallurgy, chemical industry, and food industry. The particle size of used disperse mediums – emulsions, powders, aerosols and gas-liquid systems largely determines their physical and chemical properties and is often a key parameter for evaluating the effectiveness of the equipment such as dust removal devices, emulsifiers, sprays, centrifuges [1–3]. It should be noted that the particle size (dust, aerosols, drug ingredients and dietary supplements) is the most important factor in determining their impact on the human body [4].

The technology progress has led to development of a fundamentally new approach to dispersed composition determination. It is based on measuring sizes of microparticles by their images. The progress of computer technology has greatly accelerated image analysis process and made it much less labor-intensive. This method, unfortunately, is not free of problems associated with noisy images, the heterogeneity of their illumination, the presence of shades on the measured object, etc.

Problem statement. A separate problem is the presence of agglomerated, aggregated particles, which significantly complicates the process of measurement and leads to a significant distortion of the results; so much attention is paid to the solution of this problem [5–8]. Known approaches to solving the problem of aggregate formation decomposition are based on the analysis of object geometry using morphological approaches, the shades as a source of information about the study group of overlapping objects, intensity fluctuations in contact area and other approaches. Excessive refinement of objects, sensitivity to noise and significant computational cost, as well as the impossibility to separate units consisting of a large number of particles with sufficient accuracy – these and other drawbacks complicate practical application of these methods. A separate problem is segmentation of units with low convexity defect consisting of a large number of particles, and segmentation formations consisting of objects with a high degree of overlap.

The objective of this study is to provide a research-based comprehensive method for determining the geometric characteristics of aggregated elements of dispersed formations (emulsion drops) which is resistant to image noises and is able to segment aggregates of complex configuration, both by determining points of particle contact, analyzing the aggregate structure and by marking particles when it is impossible to find contact points with the necessary precision (in the case of a small convexity defect or presence of internal particles). Light spots on the drops surfaces can serve as such markers.

Methodology. At the first stage the image is filtered. It is cleared from high-frequency noises and transferred to a monochrome mode. The process is based on threshold segmentation algorithm with a sliding window involving calculation of adaptive brightness threshold T for each pixel with coordinates (x_0, y_0)

$$T(x_0,y_0)=\frac{1}{W*H}\sum_{y=y_0-H/2}^{y=y_0+H/2}\sum_{x=x_0-W/2}^{x=x_0+W/2} g(x,y),$$

where W is width; H is height of a sliding window.

The next step is to determine coordinates of the aggregate contour points. For correct identification of objects whose contour is crossed by the image frame (Fig. 1, *a*) in order to avoid errors due to the addition of excess space, the authors propose to consider each of these figures twice, taking into account the additional image area between the object contour and frame – type “B” aggregate (Fig. 1, *c, d*) and without it – type “A” aggregate (Fig. 1, *b*) and then select the image which is the most adequate to the real object.

The main feature of the images of dispersed structures is uneven lighting, noisiness and low contrast. Therefore, the method of adaptive threshold selection is not always useful as well. Sometimes it leads to gaps in objects’ contours in an obtained monochrome picture. That is why it is advisable to correct selected contours [9] by clarifying the threshold based on brightness analysis.

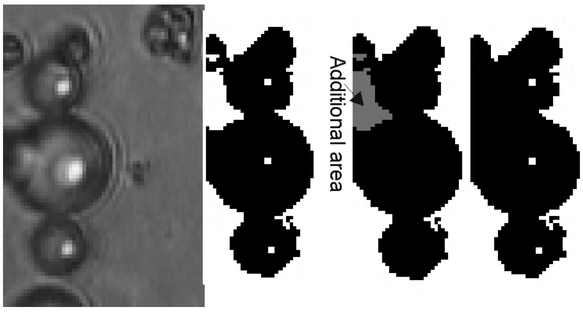
The conclusion about the success of correction may be made by comparing the geometric parameters of the unit, calculated from the contour on the basis of previous and new thresholds.

$$P_1 < P_0; \tag{1}$$

$$\left|\frac{P_1 - P_0}{P_0}\right| < 0{,}1, \quad \left|\frac{S_1 - S_0}{S_0}\right| < 0{,}1, \tag{2}$$

where P_0, S_0 are the perimeter and area of the figure measured by the results of adaptive threshold segmentation; P_1, S_1 are the perimeter and area measured by the adjusted threshold value.

A common defect of contour segmentation is “transformation” of the circle (drop contour) (Fig. 2, *a*) in the crescent (Fig. 2, *b*), whose perimeter is much greater than the perimeter of the respective circle. Therefore, a decrease in perimeter (1) indicates a successful solution of this problem (Fig. 2, *c*). A large increase in the area, on the contrary, indicates overvalued



a *b* *c* *d*

Fig. 1. Analysis of the aggregates touching the image border:

a – source object; b – type “A” aggregate; c, d – type “B” aggregate. Aggregates markers are indicated by the dots

a *b* *c*

Fig. 2. Closing the gaps by correcting the contour of water drop in the oil:

a – the original image; b – monochrome image before contour correction; c – resulting image of a drop contour

threshold, resulting in a connection of the noises to the object – unrelated areas. Criteria (2) limit the growth of the area and perimeter.

The next step is to mark aggregate particles. Light flares on the surfaces of water-oil emulsion drops can act as such markers. This marking allows decomposing aggregates with low defect of convexity if structure analysis [10] is not effective and/or in the presence of internal particles.

Heterogeneity of substance of a drop and the inclusion of foreign objects can lead to various optical effects on the drop surface, leading to fanciful flares (Fig. 3).

To use the flare as a marker, it is necessary to prevent its decomposition. So we must filter the object in order to clean flare image from the noise and make it more uniform. Then we can take flare centers as markers.

The information about the markers can be used not only for aggregate decomposition, but also for the correct identification of objects, whose contour is crossed by an image frame.

Thus, if the contour of “B” aggregate has more glares than the corresponding “A” aggregate, this fact indicates that one or more drops within the aggregate are cut by frame (Fig. 4). In this case, the “A” unit is removed and, instead, “B” unit is used for further analysis. If the connection of an additional field has not led to an increase in the number of markers, we can say that the added area in “B” unit corresponds to the background (Fig. 1). In this case, “A” unit is kept for further analysis.

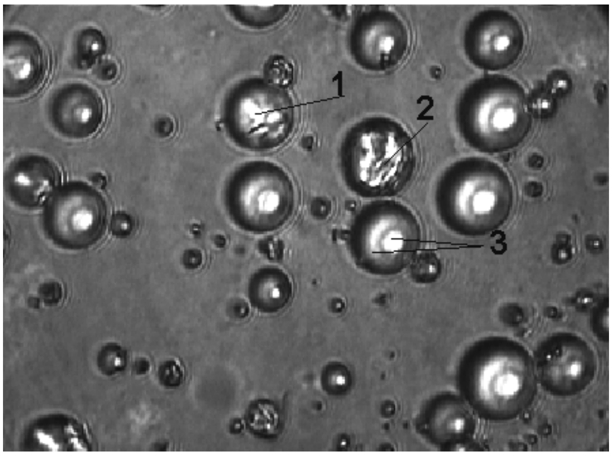


Fig. 3. The image of a water-oil emulsion:

1–3 – optical effects when light passes through a drop

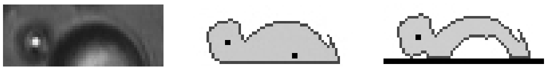
The skeleton of the aggregate is constructed from the points of the refined contour. It allows obtaining general information about the aggregate structure. The proposed method for skeleton construction includes the following steps: building a pilot skeleton based on Zhang-Suen algorithm, removing redundant connectivity, finding reference points and presenting the skeleton as a set of branches between reference points, refining the skeleton structure to represent the branch by line segments, ordering branches according to advancing from the periphery to the center of the aggregate.

Drop attachment points are defined as the “narrowest” places of the considered aggregate – the isthmuses $Q_1^{(1)}Q_2^{(1)}$, $Q_1^{(2)}Q_2^{(2)}$, $Q_1^{(3)}Q_2^{(3)}$ – Fig. 5.

To do this, we build perpendicular AB at each point P of the considered skeleton branch, and find the point of its intersection P_1, P_2 with the aggregate contour. We call P_1P_2 the inner part of the perpendicular. Since the isthmuses are the narrowest parts of the aggregate, perpendiculars corresponding to them have the shortest internal parts.

However, unit nonconvexity complicates the problem, because in general the line can cross a non-convex object in more than two points. In this case, the search of isthmus requires a special method. A detailed description of this method is presented in [10].

For efficient segmentation of internal elements and aggregate fragments formed by several drops with high overlapping, when the search of connection points is not effective, it is advisable to supplement this method



a *b* *c*

Fig. 4. Analysis of the aggregates, cut with an image frame:

a – the image of the original object; b – the image without taking an additional area (“A” type unit); c – the image with an additional area (“B” type unit). The points indicate markers

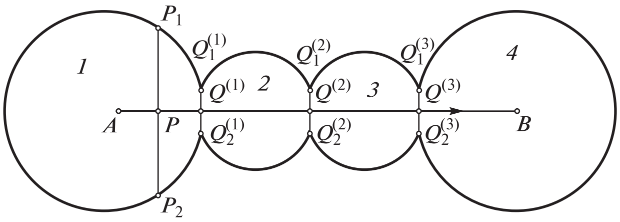
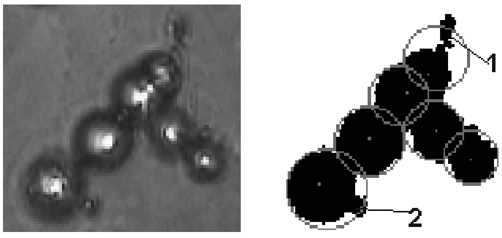


Fig. 5. The general scheme of aggregate decomposition:

AB – skeleton branch; P – an arbitrary point of AB branch; P_1, P_2 – the points of intersection of the contour and perpendicular to AB at point P; $Q^{(1)}$, $Q^{(2)}$, $Q^{(3)}$ – the points where aggregate width function is minimal; $Q_1^{(1)}Q_2^{(1)}$, $Q_1^{(2)}Q_2^{(2)}$, $Q_1^{(3)}Q_2^{(3)}$ – the point of drop connection; 1–4 –the number of drops with markers [9]. In this case the number of markers corresponds to the number of drops in the unit. For example, if the unit or a fragment contains only one marker, we can say that it contains a single drop, several glares indicate the presence of several drops and aggregate area may be distributed between them according to Voronoi diagram. Each particle corresponds to a certain diagram cell. The particle radii can be calculated from the area and the perimeter of the corresponding diagram cell. The method of constructing Voronoi diagram on the base of marker points in non-convex area was considered in [9].

Some drops may have no glares, so it is advisable to combine these two methods. Thus, application of marking technique to the object in Fig. 6 without analyzing its structure leads to errors in segmentation of the fragments *1* and *2*, which contain no glare, while a combination of these methods can eliminate this disadvantage.

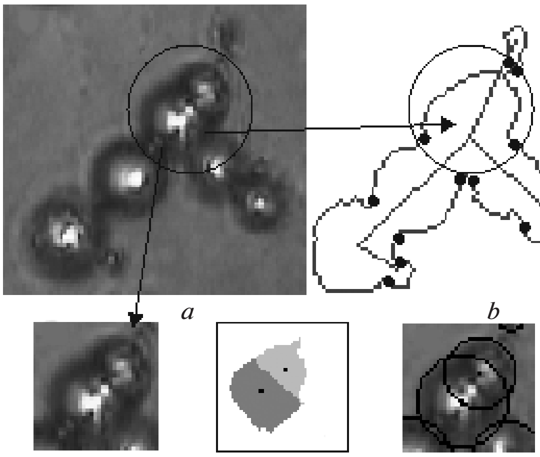
Analysis of the aggregate structure allows selecting the point of particle attachment (Fig. 7, *b*). Decomposition of the aggregate according to these points provides adequate segmentation of the drops, including non-glaring drops. Analysis of this unit is difficult because of the section with low convexity defect (Fig. 7, *c*). The use of the marker method followed by distribution of the area according to Voronoi diagram (Fig. 7, *d*) provides adequate segmentation of this object (Fig. 7, *e*). The segmentation of the whole unit made by the complex method combining the analysis of the structure with markers placement is shown in Fig. 8.



a *b*

Fig. 6. Decomposition of the unit by marking drops without analyzing the structure:

a — the original image; b — the resulting image; points represent the particles markers; 1, 2 — fragments with segmentation inaccuracy



a *b*

c *d* *e*

Fig. 7. Decomposition of type II emulsion (water in oil) image:

a — the original image; b — the image with attachment points; c — segment with low defect of convexity; d — separation of Fig. 7, c by means of Voronoi diagram; e — segmentation of Fig. 7, c; square points represent the particle markers, round points — drop connections

The described method of aggregate separation is illustrated by the image of type II emulsion — Fig. 9.

Conclusions. The problems of image processing are heterogeneity of lighting, noisy background and low contrast. While measuring microobjects, the presence of aggregated structures often leads to significant errors in dispersed composition evaluation.

The authors developed a complex method for evaluating geometrics of emulsion drops and other dispersed formations of spherical particles considering their aggregation. The method is based on the aggregate structure and contours, using marking of analyzed objects.

The method includes several steps: image filtering, converting it to a monochrome mode, evaluating the aggregate contour, correcting the contour, setting particle markers according to glares on particle surfaces, making the skeleton, introducing the function for each skeleton branch, which characterizes the width of cor-

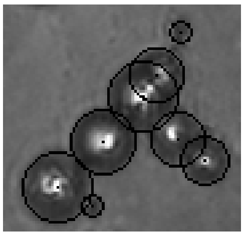
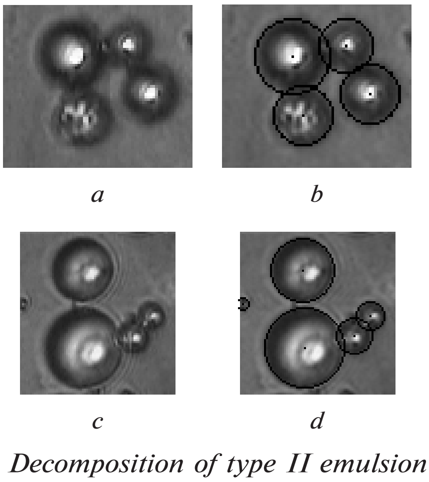


Fig. 8. Segmentation of the aggregate shown in Fig. 7, a by analyzing its structure and marking particles



a *b*

c *d*

Fig. 9. Decomposition of type II emulsion (water in oil) images:

a, c — original images; b, d — results of segmentation

responding aggregate portion, determinating connecting points as local minimums of this function. To decompose aggregate fragments containing several markers, the aggregate's area is distributed between the particles according to the Voronoi diagram. Parameters of circles corresponding to particles are evaluated from geometrics of corresponding aggregate fragments.

The method is illustrated by the images of real emulsion fragments (type II emulsions – water in oil)

The developed method allows realizing segmentation of complex structured aggregates consisting of many spherical particles, containing internal objects whose contour is located entirely inside the aggregate. The number of incoming particles is not limited.

The method may be used to evaluate dispersity of emulsions and other finely divided materials at various industries.

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Розмір частинок, у значній мірі, визначає властивості дисперсних матеріалів і є вирішальним параметром при оцінюванні ефективності обладнання. Наявність агрегованих частинок істотно ускладнює процес вимірювань.

Мета. Створення комплексного методу визначення геометричних характеристик крапель емульсій та інших дисперсних частинок сферичної форми з урахуванням їх агрегування, заснований на інформації про структуру та контур агрегату, із застосуванням маркування аналізованих об'єктів.

Методика. Метод включає кілька етапів: фільтрація зображення та переведення його до монохромного режиму, визначення контуру агрегату, корекція виділеного контуру, розстановка маркерів частинок за відблисками на їхній поверхні, побудова скелету, визначення точок приєднання частинок. Для декомпозиції фрагментів агрегату, що містять декілька маркерів, розподіл площі фрагмента агрегату між частинками, що входять до його складу, здійснюється шляхом побудови діаграми Вороного. Параметри окружностей, відповідних зображень частинок, визначаються за геометричними характеристиками відповідних їм фрагментів агрегату. Метод проілюстрований на фрагментах зображень реальних емульсій другого роду (вода в маслі) .

Результати. Розроблений метод дозволяє здійснювати сегментацію агрегатів складної конфігурації, що складаються з частинок сферичної форми та містять внутрішні об'єкти, контур яких розташовується цілком усередині агрегату, без обмежень на число частинок.

Наукова новизна. Розроблено метод сегментації агрегованих елементів дисперсних утворень (крапель емульсій), що є стійким до шумів зображення та дозволяє здійснювати сегментацію агрегатів складної конфігурації як шляхом визначення точок контакту частинок агрегату за даними про його структуру, так і шляхом маркування частинок у випадках, коли знаходження точок приєднання з необхідною точністю неможливе (у разі малого дефекту опуклості або наявності внутрішніх частинок). Такими маркерами можуть виступати світлові відблиски на поверхні крапель.

Практична значимість. Метод може бути застосований для визначення ступеня дисперсності емульсій та інших тонкоподрібнених матеріалів у різних галузях промисловості.

Ключові слова: *агрегат, дисперсні утворення, сегментація, діаграма Вороного, маркери, точки приєднання частинок*

Размер частиц, в значительной степени, определяет свойства дисперсных материалов и является решающим параметром при оценке эффективности оборудования. Наличие агрегированных частиц существенно затрудняет процесс измерений.

Цель. Создание комплексного метода определения геометрических характеристик капель эмульсий и других дисперсных частиц сферической формы с учетом их агрегирования, основанного на информации о структуре и контурах агрегата, с использованием маркирования анализируемых объектов.

Методика. Метод включает следующие этапы: фильтрация изображения и перевод его в монохромный режим, определение контура агрегата, коррекция выделенного контура, расстановка маркеров частиц по бликам на их поверхности, построение скелета, определение точек присоединения частиц. Для декомпозиции фрагментов агрегата, содержащих несколько маркеров, распределение площади фрагмента агрегата между входящими в него частицами осуществляется путем построения диаграммы Вороного. Параметры окружностей, соответствующих изображениям частиц, определяются по геометрическим характеристикам соответствующих им фрагментов агрегата. Метод проиллюстрирован на фрагментах изображений эмульсий второго рода (вода в масле).

Результаты. Разработанный метод позволяет осуществлять сегментацию агрегатов сложной конфигурации, состоящих из частиц сферической формы, содержащих внутренние объекты, контур которых располагается целиком внутри агрегата, без ограничений на число входящих частиц.

Научная новизна. Разработан метод сегментации агрегированных элементов дисперсных образований (капель эмульсий), устойчивый к шумам изображения и позволяющий осуществлять сегментацию агрегатов сложной конфигурации как путем определения точек контакта частиц агрегата по данным о его структуре, так и путем маркирования частиц в случаях, когда нахождение точек соприкосновения с необходимой точностью невозможно (в случае малого дефекта выпуклости или наличия внутренних частиц). Такими маркерами могут выступать световые блики на поверхности капель.

Практическая значимость. Метод может быть применен для определения степени дисперсности эмульсий и других тонкоизмельченных материалов в различных отраслях промышленности.

Ключевые слова: *агрегат, дисперсные образования, сегментация, диаграмма Вороного, маркеры, точки присоединения частиц*

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