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An original technique for quantifying the flow-field characteristics in an electrodeposition process of Zn-SiO₂ with Fe

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Abstract

The purposed of this article is to introduce a novel approach (uniformity measure, U) based on entropy theory for measuring the micron-particle blend homogeneity of aqueous electrolytes, which applies directly to the imaging data of flow field and does not require contacting and disturbing it. Effectiveness of the new method has been illustrated on synthetic imaging data. To verify the feasibility of our method for real experimental data, we analyze the flow-field images from electrodeposited Zn-Fe-SiO₂ composite coatings process. The numerical results showed that the potential of proposed method was demonstrated successfully to quantitatively establishes association between plating parameters and flow field characteristics. The possible recommendations are to monitor the deposition of micro-particles during the composite electrodeposition processes and to apply this technique for studying a variety of multiphase mixing problems in which assessment of uniformity is required.

Keywords: flow-field characteristics; composite electrodeposition; uniformity measure; plating parameters;

Zn-Fe-SiO₂.

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1. Introduction

As one of the most significant metallic material surface finishing technologies and metal-based composite material preparation technologies, composite electrodeposition plating technology is widely adopted to prepare the new chemical materials with satisfactory performance [1, 2, 3, 4]. In particular, it is one of most commonly practiced industrial techniques for the fabrication of zinc coatings which are widely used for the corrosion protection of ferrous materials, acting both as a physical barrier from the surrounding corrosive environment and as a self-sacrificial anodic protective layer [5, 6, 7, 8]. There are two basic types of Zn and Zn alloy plating baths currently available: acid and alkaline type [9, 10, 11]. Blend homogeneity is key to composite electrodeposition, and researchers put substantial resources into inspiring flow field to develop mixing uniformity. Zinc is a well-known sacrificial coating material for iron and co-deposition of suitable particles is of interest for further improving its corrosion protection performance [12, 13, 14]. Electrodeposition of zinc-iron alloys is of practical importance since they have better corrosion resistance and mechanical properties than pure zinc coating [15, 16]. Although some of the open research focused on electroplating technological parameters and electrochemical theory, the number of publications which address the quantification of flow-field characteristics of electrolyte solution is very limited [17].

Studies show that the mixing quality of electrolyte solution and the electrochemical reaction on the surface of are important for appraising performance of composite electrodeposition. However, the reports have not been completely able to provide a quantitative interpretation of mixture. Khan et al. (2011) reported a detailed study of Zn-SiO₂ nanocomposite coatings deposited from a zinc sulfate (ZnSO₄) solution at pH=3 [13]. Shahri et al. (2013) prepared a new nanocomposite coatings by means of the conventional electrodeposition in chloride solution containing different concentrations of hexagonal boron nitride particles [18]. Xia et al. (2013) investigated the microstructure of Ni-AlN composite coatings prepared by pulse electrodeposition technology [19].

Although material or fluid images contain a huge array of data about the identity, position, intensity and distribution of chemical species on a surface, processing these images to obtain concise electrochemical information can be a formidable challenge [20, 21, 22]. Image processing technique with advanced statistical

methods or other mathematical theories is gaining in importance for feature extraction [23, 24, 25, 26].

Zaborowski et al. (1995) developed a method for quick comparison of the quality of an Al surface by digital

image processing [27]. Lapsker et al. (1996) used two topological analysis, including fractal dimensionality

and 2D-Fourier spectral analyses, for classifying the surface morphology in the various zones of the laser

beam written thin film [28]. Coënt et al. (2005) showed an original image-processing technique for obtaining

the mixing time: The box-counting with erosions method. Oshida et al. (2013) observed the space structure

of the nanotubes by 3D-TEM and revealed the detailed structure by HRTEM, which is useful to understand

the nano-structure of materials accurately [29]. Recently, we showed an image analysis technique combined

with two statistical hypothesis-testing tools including Kolmogorov-Smirnov test and χ^2 test to obtain the

p -values for bubble images comparison [30].

Analysis of images from flow field have been made so far, although they are limited to qualitative or semi-

quantitative analyses. The information in such an image is very useful in terms of position and intensity.

Positions of images show the structure of the material. In order to learn about the accuracy of images,

quantitative analysis of images is necessary. From the foregoing it is seen that the technique presented

in this current article represents an extension of our tools in the field of the mixing characterization of

electroplating bath composition. This study mainly focuses on the blend homogeneity of electrodeposition

flow field.

The contributions of this work are two-fold. First, from flow field analysis point of view, our proposal

timely responds to a number of growing needs of quantitative characterization of subjective human

experience. Second, from a composite electrodeposition point of view, our proposal develops a general

framework for understanding association between plating parameters and flow field characteristics.

Furthermore, using the mixing uniformity coefficient as the observable, one can take recordings for a

interval of time. The 0-1 test method [31, 32] and three state test (3ST) [33, 34] could be employed for

chaos detection of the flow field once the time series data can be obtained.

The rest outline of the article is organized as follows. In the next section, the experimental setup and the

scheme of the proposed methodology are presented. Then the results and discussion are shown in Section 3

while the conclusions are briefly summarized in Section 4 finally.

2. Experiments and methodology

2.1. Experimental details

Figure 1: Schematic diagram of experimental electrodeposition apparatus (a: the bath composition consists of chloride and SiO_2 particles; the Zn sheet represents the anode whereas the Fe sheet represents the cathode; a mixing picture corresponding to the mixed state of electrolyte solution at $s=1$ cm, $I=0.5$ A, $r=1000$ rpm and $h=10$ mm) and PIV images reported by Ref. [35] (b: considering different I and r at $h=10$ mm).

In this present research, the procedure of zinc-silica (Zn-SiO_2) composite plating consists of: (a) fore-treatment of matrix; (b) plating; (c) rinsing; (d) dry. The schematic diagram of the acquisition system and the reactor is shown in Fig. 1. The length L , width W , and height H of the cubic reactor were 150 mm, 100 mm and 120 mm, respectively. Electrodeposition experiments were performed at room temperature

(25°C±2°C) using zinc chlorate-based electrolytes, containing ZnCl₂ (80 g/L, as base fluid), KCl (220 g/L), H₃BO₃ (25 g/L), brightening agent (0.5 g/L) and SiO₂ particles (1 g/L, average particle size is 11.07 μm) and its pH value was 5.5. More specifically, the materials used for our electrodeposition experiments were chemical analytic pure, which were all purchased from Tianjin Fuchen Chemicals Reagent Factory (Hebei, China). The viscosity and density of the electrolyte solution were regulated using the viscosimeter and the weighing method, respectively. The solution conductivity and surface tension were measured using the conductivity meter and surface tension tester, respectively. The stirring rate of the electric stirrer and the electric current of the electrodeposition device are kept in the range of 0~3000 rpm and 0~0.5 A, respectively. The size of stirring paddle was 2 mm×10 mm×6 mm, whereas the height of paddle was 10~30 mm. The cathode was an iron plate and the anode was a zinc plate. In this work, the physical characteristic parameters were also obtained. For instance, the density of electrolyte (1.16~1.18 g/cm³) was determined by the weighting method; solution conductivity (0.75~0.95 μs/cm) was measured by a conductivity meter; surface tension (40.5~41.0 mN/m) was determined by a surface tension tester; the dynamic viscosity (1.50~1.52×10⁻³Pa·s) and kinetic viscosity (1.51~1.53×10⁻⁶m²/s) were measured by a viscometer and the size of SiO₂ particles (around 10μm) were determined by a laser particle size analyzer.

For the sake of employing similar materials, some more details of experimental setup for electrodeposition and design parameters with different levels are present in Ref. [36, 35]. As listed in above references, four different parameter, including the distance between the cross section tested by PIV and cathode s (unit: cm), stirring rate v (unit: rpm), electric current I (unit: A) and the height of paddle h (unit: cm), were used to investigate the blend homogeneity in the Zn-Fe-SiO₂ electrodeposition process. The operating parameters of the vessels used in this work are summarized in Table 1.

Table 1: List of experimental conditions investigated with PIV in electrodeposition reactor.

Description	Parameter	Level			Unit
		1	2	3	
Current	I	0	0.25	0.5	A
Distance	s	1	3	5	cm
Height	h	10	20	30	mm
Velocity	r	1×10 ³	2×10 ³	3×10 ³	rpm

Table 2: Design experiments of experimental cases according to previous work.

Cases	$I(\text{A})$	$s(\text{cm})$	$h(\text{mm})$	$r(\text{rpm})$	$t(\text{s})$
C ₁	0.5	5	10	3×10^3	10
C ₂	0.25	5	20	2×10^3	20
C ₃	0	5	30	1×10^3	10
C ₄	0.25	3	30	3×10^3	20
C ₅	0	3	10	2×10^3	10
C ₆	0.5	3	20	1×10^3	20
C ₇	0	1	20	3×10^3	10
C ₈	0.5	1	30	2×10^3	20
C ₉	0.25	1	10	1×10^3	10
C ₁₀	0	1	10	2×10^3	20
C ₁₁	0.25	1	10	2×10^3	10
C ₁₂	0.5	1	10	2×10^3	20
C ₁₃	0	1	10	0	10
C ₁₄	0.25	1	10	0	10
C ₁₅	0.5	1	10	0	10

In the previous work, Ref. [3] recorded the actual flow state by Particle Image Velocimetry (PIV), as well as finishing the numerical simulation of flow field of Zn-SiO₂ composite electrolyte by FLUENT software. It is worth to remark that 15 samples selected from the experiment cases were recoded repeatedly (10 s, 20 s or 30 s) in order to investigate the blend homogeneity of electrolyte solution. In this current work, the symbols and numbers C₁-C₁₅ denote different experimental levels, as shown in Table. 2.

2.2. Mixing images acquisition

PIV test is one of the highest resolution analysis methods for investigating flow-field characteristics. The obtained mixing images were recorded on high-speed video camera (PRAKTICA from Germany) whose dynamic intensity range is from 10^3 to 10^4 , which is enough for the present investigation. A typical image of the vessel obtained by the above described apparatus is shown in Fig. 1a. Digital image processing technology was employed to deal with the real-time images of mixing particles in the flow field of electrodeposition experiment into the computing objective below. Subsequently, the picture was quantitatively measure with a resolution of 1200×1200 . The digitalized intensity was processed by personal computer (PC) and displayed in various forms.

The proposed measure of uniformity is based on a novel core idea in terms of that how to define uniformity of an image. Generally speaking, the image rapidly collected and stored by currently available instrumentation contains the full mass spectrum at every image pixel. Like hypothesis testing in statistics, assuming an α smaller than the instantiated p -value will end up not rejecting the null hypothesis. Hence, the content of information was inversely associated with probability P of the events and the novel core idea is that if the image has many regular blend, the image uniformity will be more worse (see Fig. 2, a counterexample). The description of the original technique follows in detail.

Figure 2: Illustration of three most uniform synthetic images (corresponding to $U = 1$) of mixing system obtained by three computer experiments (left: 32×32 ; middle: 64×64 ; right: 128×128).

Definition 1. Generally, for two unrelated events, it is expected that the occurrence of one does not affect the information content of occurrence of other. In order to define a function f_0 for information content of a point set, the logarithmic function $\log$ of P is therefore given by:

$$f_0(P) = -\log_a(P) \quad (1)$$

Definition 2. In particular, for an gray-scale intensity image its *image entropy* indicated by f_1 is given by:

$$f_1 = E(f(P_c)) = \sum_{i=0}^{255} P(c_i) f(P(c_i)) \triangleq - \sum_{i=0}^{255} P_i \log_{256}(P_i) \quad (2)$$

where c_i represents the i th gray-scale intensity from 0 to 255 and $P(c_i)$ represents the probability of

occurrence of c_i . However, not all gray-scale intensity between 0 and 255 exist in a digital image for some real-world applications, as shown in Fig. 3a.

Figure 3: The statistical image analysis (a: gray-level histogram and Normal probability density function, b: perspective view of intensity distribution) and the average gray level (c: in the column direction; d: in the row direction) of a gray-scale image at the top-right corner of Fig. 1 corresponding to the mixed electrolyte solution.

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Definition 3. Inspired and motivated by previous section, we introduce an alternative approach, *modified image entropy* method for this situation to improve the uniformity metric. Let

$$B = (b_1, b_2, b_3, \dots, b_m) \in \Delta_m, \quad (3)$$

where

$$\Delta_m = \{(b_1, b_2, \dots, b_j, \dots, b_m) | b_j \geq 0, m \geq 2, \sum_{j=1}^m b_j = 1\} \quad (4)$$

is a set of discrete finite m -ary probability distributions. The *modified image entropy* indicated by g is given by:

$$g = E[f(P_b)] = \sum_{j=1}^m P(b_j) f(P(b_j)) = - \sum_{j=1}^m P_j \log_m(P_j) \quad (5)$$

where b_j denotes the j th gray-scale intensity existed in the set of positive integers $\{0, 1, 2, \dots, 255\}$. In particular, the most uniform cases occurs when all (corresponding to $g = 1$, $P(b_1) = P(b_2) = P(b_m) = \dots = \frac{1}{m}$), whereas the most non-uniform case occurs when all the pixels are at the same level (corresponding to $g = 0$).

Definition 4. According to the previous analyses, our uniformity measure function indicated by U must focus on that U should increase but not outnumber 1 as the uniformity of mixture distribution improves. Moreover, the uniformity measure should also be dependent on the position of pixels. So the homogeneity index of the local mixing system based on direct imaging technology is shown as below:

$$U = 1 - \frac{1}{K-1} \sqrt{\sum_{k=1}^K (g_k - \bar{g})^2} \quad (6)$$

110 where g_k is the g value of the pixels in the segmented region R_k (one picture strictly consists of K independent rectangle pieces R_k , $k=1, 2, \dots, K$), and $\bar{g}$ is the average of g_k . Generally speaking, the uniformity index of the entire image is the standard variation of all parts of the image. Simply, higher level of U indicates better homogeneity. Fig. 2 shows three synthetic images of different pixels all corresponding to $U=1$. Obviously, synthetic images were produced with a homogeneous distribution of pixels on the entire surface of the image.

115 3. Results and discussion

In this section, experimental results of applying the proposed method to the experimental images along with the statistical analyses and comparison with other existing method are reported. The following

calculations are all performed by using MATLAB R2014a on a PC with Intel(R) Core(TM) i5-6300HQ 2.30 GHZ processor. For qualitative and quantitative analysis of performance of the proposed method an gray-scale photograph and some FLUENT images are considered. The dimension of all the images are 1200×1200 .

3.1. Transient analysis of the mixing patterns

Statistical image analysis was employed to study the mass transfer. In the top-right corner of Fig. 1a, a mixing pattern which is a real example of mixed region was shown at a given moment in the electrodeposition experiment. It can be seen that the highly intense regions in this observation are saturated. As shown in Fig. 3a, a bell shaped distribution of the mixing pattern was obtained. However, this is made to show weak SiO_2 particles clearly and the real picture does not saturate. In order to improve this, a perspective view of the intensity distribution is given in Fig. 3b corresponding to the above image. Fig. 3c shows the average gray level in the column direction while Fig. 3d shows the average gray level in the row direction. We found that the average gray level increases at one end and increases or decreases at the other end, while they become stabilised on the central regions due to the homogeneity of the mixture. Therefore, we get a qualitative and semi-quantitative evaluation result that is in line with subjective perceptive quality.

From Fig. 4, we obtained $U=0.9507$ which is closer to 1. It is indicated that this mixing transient is homogeneous. On the other hand, we investigated the core equation (5) in detail in this part of the study. We applied the uniformity measure U with different input parameter m to the mixing picture obtained by our camera. Fig. 4 also represents the effect of varying the current base number of input parameter on the homogeneity evaluation of mixing picture. By increasing the base number from 1 to 256, the U rose as a whole. It can be noticed that the higher the base number, the higher the value of U before $m=161$. For $m=256$, f_1 is smaller than U . According to above data and curves, the base number has an important influence on uniformity measure. It is important to select a very suitable parameter to understand the uniformity ranking and the influence degree of operating parameters on the mixing effect of electrolyte solution. Meanwhile, we believe that the high value of U is associated with the fluid flow between the various compounds. Indeed, the mixing can be considered as completely homogeneous when the uniformity

Figure 4: Effect of the common base number (namely, m in Eq. 5) on modified image entropy and uniformity measure (namely, U in Eq. 6) for the real CCD picture of electrolyte solution in Fig. 1a. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

measure U reaches a value which nearly equal to 1 (about 0.9).

3.2. Experimental verification of the measure

To investigate the effect of flow-field characteristics of electrolyte solution on electrodeposited zinc-silica composite plating, the PIV system was used to record and test the actual flow field of zinc-silica composite electrolyte, as shown in Fig. 5a and Fig. 5b which corresponds the experimental cases of C_9 ($I=0.25$ A, $s=1$ cm, $h=10$ mm, $r = 1000$ rpm) and C_{11} ($I=0.25$ A, $s=1$ cm, $h= 10$ mm, $r = 2000$ rpm) at $t=10$ s, respectively. However, it actually provided incomplete pictures in nearly all the experiments because a few portion of particles were not captured by the video camera. According to Ref. [3], the numerical simulation of flow-field of zinc-silica composite electrolyte has been finished by FLUENT software (for example, Fig. 5c and Fig. 5d which corresponds to the same experimental conditions as Fig. 5a and Fig. 5b, respectively.). Fan et al. also reported that the simulation results of flow field was approximately similar to the actual flow state and the contrast results proved the reliability of numerical simulation. To test the validity of

this technique, therefore, those simulation images could be employed for measuring mixing uniformity of electrolyte solution instead of PIV images and had the uniformity measure calculation results with $U=0.8743$ and $U=0.7430$, respectively. It is obviously that the former case exhibits better mixing uniformity than the other one.

Figure 5: Real images recorded by PIV system (a and b), simulation images obtained by FLUENT software (c and d) and SiO₂ content distribution tested by an electron probe (e and f) from two experimental cases C₉ and C₁₁. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

160 In order to further verify the degree of correctness of the procedure of novel statistical evaluation, several measurements have been conducted with the assistance of electron probe testing, a magnetic thickness tester, and an erosion test[37, 35]. Closer inspection on Fig. 5e and Fig. 5f, it is noticed that SiO₂ is well

distributed in the first cases, and there is clearly some empty area in the second one which proves that the flow field mixing is not so balanced. This qualitative judgment was quantitatively demonstrated according to this current work. In addition, Table 3 presents three performance parameters, including silica content in composite coatings, thickness of coatings and red rust time in Neutral Salt Spray (NSS) time, of composite coatings in 9 sites of plated steel sheet for two different experimental cases C_9 and C_{11} . It can be seen that C_9 outperforms C_{11} at all the sites from the standard deviation (SD) average analysis point of view.

Table 3: Three performance parameters of composite coatings in 9 sites of plated steel sheet for two different experimental cases.

Sites	SiO ₂ content in composite coatings [%]		Thickness of coatings [μm]		Red rust time in NSS test [h]	
	C_9	C_{11}	C_9	C_{11}	C_9	C_{11}
1	0.48	0.63	22.00	23.40	440	409
2	0.50	0.51	20.90	21.30	424	409
3	0.50	0.36	22.25	18.65	440	389
4	0.51	0.61	21.50	22.40	424	424
5	0.52	0.54	20.65	21.65	416	432
6	0.52	0.38	21.70	19.50	424	393
7	0.54	0.44	21.95	20.40	440	401
8	0.56	0.51	21.65	21.20	424	417
9	0.55	0.60	22.30	23.70	448	424
SD	0.05	0.08	0.25	1.56	11.31	5.66
Average	0.52	0.51	21.66	21.36	431	411

3.3. Uniformity ranking of mixing transient

As above section, the image databases photographed by PIV in this work could not be complete due to the limitation of experiment conditions, and the flow-field character of Zn-SiO₂ composite electrolyte has been investigated by computer simulations [3]. Performance comparison between the novel technique and the existing method was therefore carried out by means of the data from the numerical simulation experiments in this current part. Based on the results obtained from the previous work, performance comparison in the application of numerical simulation results ranking will be limited to the traditional fractal dimension D [38], maximum relative velocity v_{max} and the proposed uniformity measure U . Specifically, this section presents the new engineering application of uniformity measure in the field of numerical simulation. The proposed measure is an original method of characterizing dynamic behaviors of electrolyte under the different stirring

conditions. From Fig. 6a, the comparison of U with $v_{\max}$ can be seen for 15 experimental cases while Fig. 6b

shows the comparison of U and D .

According to this figure, it is obvious that the zig-zag patterns of the three curves are very close and the differences in them are evident in case of some individuals. The difference in patterns of zig-zag can be interpreted as follows: theoretically speaking, the quality of mixing state and the relative velocity of flow field tend towards congruency and the changes in maximum relative velocity shows the variations in mixing state of the flow field; fractal dimension D , the measure of complexity and the proposed mixing index U , the measure of uniformity can be used to characterize the quality of mixing state of the flow field; U and D have a significant and relatively high sensitivity because the concept of fractal dimension can also be used to quantify the deviation from the uniformity distribution. However, the precise definition of fractal dimension is actually very difficult to determine because the calculations of different fractal dimensions are commonly based on different application backgrounds. Closer inspection shows that the proposed uniformity measure U is capable of ranking the simulation images in an order that is agreeable to the $v_{\max}$ and D for experiments C_1 - C_7 and C_{13} - C_{15} . Those demonstrated that the relationship between mixing uniformity and flow-field characteristics could be explored by U from the viewpoint of experimental analysis. Furthermore, it is interesting to note that the peak value was obtained at the same experimental case C_4 (see green circle and rectangle in Fig. 6a and Fig. 6b, respectively) by all the three approaches. This indicates that uniformity measure U can be an alternative route to design an optimal plating procedures. The reason is that the influence of time space and position information on mixing quality is not taken into account in the traditional assessment methods of Betti numbers. In research process, we found that the scale of structure features has significant impact on the subjective perceptive quality of mixing system. Therefore, as a pixel-based evaluation approach, the proposed technique has showed good performances for electrodeposition system.

3.4. Characterization of the mixture homogeneity

For investigating the characterization of the mixture homogeneity in electrolyte solution, we will now use this original method to study the influence of the operating conditions on the homogeneity degree of the blend of chloride and SiO_2 particles in the aqueous solution. From the experimental analyses the following

205 results are summarized:

(1) The current density of electrical field affects the mixture blend in electrolyte solution. As can be seen in Fig. 6 the mixing homogeneity becomes better with an increase of current density. For the used operating current density of 0, 0.25A and 1.5A in our experiment, the evaluation values of the mixing uniformity of electrolyte solution under different experimental conditions were between 0.68 to 0.8 which are dimensionless.

210 (2) The mixture homogeneity of the bath versus s which indicates the distance between photographed cross section and the cathode was explored. The distance had a great effect on the solution state. (3) By analysing the effect of height on mixing uniformity, it was obtained that raising the height improves the uniformity of SiO_2 particles in the bath at $t = 10$ s whereas the increase of h causes deterioration of uniformity of the bath. The operating height h range is 10 mm and 20 mm. (4) From exploring the influence of rate on the

215 mixing homogeneity, it was found that a rise of the stirring rate r decreased the homogeneity degree in the bath from $U = 0.8743$ at $r = 1000$ rpm to $U = 0.8178$ at $r = 2000$ rpm when the images were captured at $t = 10$ s. Combined with the characterization result at $t = 20$ s, it appears that the uniformity measure U also fell slightly which indicates that the solution mixing becomes worse.

4. Conclusions

220 In this paper, we introduce an original image analysis technique to be employed for investigating the visualization problem of electrodeposited Zn-Fe- SiO_2 composite bath. Based on the present experimental results and considerations of the above investigation concerning the characterization of electrolyte solution of Zn- SiO_2 composite electrodeposition, the following conclusions can be made:

(1) In order to address the problem of flow field characterization without intrusion for composite

225 electrodeposition, the methodology of the *modified image entropy* based technique for the uniformity measurement of flow field was proposed. The method shows good correspondence to computer simulated images, with known generation process, and have successfully been applied also on real images. This technique could allow a hydrodynamic characterisation of the reactor by evaluating the mixing homogeneity between micro-particles or other particles. (2) Our results confirm that the U is sensitive to

the variation of I , s , h and r which have strong influence on electrodeposited composite coatings. The experimental results show that the novel method can give reliable assessment and are well suited to describe flow field quantitatively. The theoretical results are in good agreement with the experimental data. Therefore, a lot of experiments need to be done to choose the optimum operating parameters by this proposed method. (3) This image analysis processing used here for mixture picture is interesting and effective. These studies thus offer a new strategy to other measuring techniques (electrical capacitance, NIR, etc.). However, a remark is concerning the shortcoming of the conclusions drawn employing 2D images. There is a number of growing needs to make a 2D-to-3D inference in the further work.

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Figure 6: Comparisons of uniformity measure U with maximum relative velocity $v_{\max}$ (a) and fractal dimension D (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)