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(54) Title: METHOD FOR DETERMINATION OF SPATIAL DISTRIBUTION AND CONCENTRATION OF CONTRAST COMPONENTS IN A POROUS AND/OR HETEROGENEOUS SAMPLE

(57) Abstract: A method for determination of a spatial distribution and concentration of contrast components in a porous sample comprises the steps of scanning a sample with X-ray and obtaining a computer tomographic image of the sample. Then an area of interest inside the obtained computer tomographic image is selected and a first cross-section of the computer tomographic image is defined. Spatial distribution and concentration of contrast components inside the area of interest are determined by analyzing histograms of grayness distribution in the cross-sections of the computer tomographic image starting with the reference cross-section.



Method for determination of spatial distribution and concentration of contrast components in a porous and/or heterogeneous sample

Field of the invention

The present invention relates generally to the methods for determination of spatial distribution and concentration of contrast components (mineral grains, components inside pore space, inclusions) in materials by analysing X-ray tomography data and can be used, for example, for calculation of fraction of contrast minerals in rock sample, diagnostic of tumor (cancerous or innocent) sizes in medicine (after using of special contrast agents), crack detection of composite and geo- materials.

Background of the invention

Powerful nondestructive method for analysis of contrast components in heterogeneous or porous medium is X-ray micro Computed Tomography (XmCT). This technique provides 3D object structure composed of cross-section images of the internal structure with acquisition of grayscale which represents the X-ray absorption distribution (attenuation coefficients) within the object. The idea of correlation between the gray values distribution in X-ray CT image and material densities distribution is described in US Pat. No. 2005/0010106).

Computer tomography technique is based on the interaction of X-rays with material. Passing through an object X-rays will be attenuated depending on the physical density and atomic number of the studied object and on the used X-ray energies. This attenuation information is collected on 2D XmCT image.

Depending on X-ray attenuation coefficient, each point of the black-white slice of object is characterized by different grayness. Because

attenuation coefficient depends on material, through X-ray has passed, different materials are characterized by different grayness that allow us to separate individual materials and estimate it's fraction on each X-ray section.

Most widespread method of image recognizing is thresholding. Thresholding is method to separate object of interest from "background" (i.e. other objects) which is based on choosing of optimal threshold level of grayness. All points ("pixels") of the black-white X-ray image of object which grayness is lower then the threshold value are supposed to belong to object (or background, depending what is more bright).

Special type of this method is histogram based thresholding which is developed for case when an image have only two principal ("dark" and "light") grayscale regions (see, for example, Gupta L., Sortrakul T. A Gaussian-mixture based image segmentation algorithm. Pattern Recognition, Vol. 31, № 3, p.315—325,1998).

Principle disadvantage of thresholding technique is sensitivity of results to selected value of threshold and thus requires a priori information about analyzed parametres.

This invention describes new method which is based on solving of inverse problem while analysis of histogram and provide deterministic solution.

Summary of the invention

A method for determination of spatial distribution and concentration of contrast components in a porous sample comprises the steps of scanning a sample with X-ray and obtaining a computer tomographic image of the sample. Then an area of interest inside the obtained computer tomographic image is selected and a first cross-section of the computer tomographic image (let us call it as reference cross-section and assign a number $k = 1$) is defined.

Histograms of grayness distribution in the cross-sections of the computer tomographic image are obtained. Spatial distribution and concentration of contrast components inside the area of interest are determined by analyzing histograms of grayness distribution in the cross-sections of the computer tomographic image, starting with the reference cross-section.

According to the first embodiment of the invention number of the components is defined as the number of peaks on the histogram of grayness distribution inside the area of interest on the reference cross-section. The histogram $I_i^1(z)$ of grayness distribution for each component inside the reference cross-section ($k = 1$) is approximated by normal distribution (Gaussian function):

$$I_i^1(z) = A_i^1 \exp \left[- \left(\frac{z - B_i^1}{C_i^1} \right)^2 \right]$$

wherein i is index of a component; I is “intensity” (total number of pixels) of grayness z ; A_i^1 , B_i^1 , C_i^1 are adjustable parameters; upper index “1” corresponds to number of cross-section ($k = 1$). Adjustable parameters for all components are crudely estimated from the histogram of grayness distribution inside the area of interest. Accurate estimation of adjustable parameters for the components is made by minimization of module of difference between the histogram of grayness distribution inside the area of interest of the reference cross-section and sum of normal distributions corresponding to individual components

$$\sum_{j=1}^M \left[H^1(z_j) - \sum_{i=1}^N A_i^1 \exp \left(- \left(\frac{z_j - B_i^1}{C_i^1} \right)^2 \right) \right] \rightarrow 0 \quad (1)$$

wherein j is index of grayscale; M is total number of grayscales; N is total number of different components.

The fraction a_i^1 of the individual components inside the reference cross-section inside of the computer tomographic image is calculated as:

$$a_i^1 = \int A_i^1 \exp \left[- \left(\frac{z - B_i^1}{C_i^1} \right)^2 \right] dz \quad (2)$$

Obtained parameters of Gaussians A_i^1 , B_i^1 , C_i^1 of the reference cross-section are used as initial parameters for minimization of module of difference between the real histogram of grayness distribution and it's approximation by sum of normal distributions (1) for next cross-section of X-ray image ($k = 2$) and so an.

To reconstruct the distribution and concentration of the contrast components along the sample, the minimization of module of difference between the real histogram of grayness distribution and it's approximation by sum of normal distributions (1) and the expression (2) are applied to all cross-sections inside area of interest of the computer tomographic image ($k = 1 \dots K$).

According to the second embodiment of the invention the sub-areas each containing only one individual component are selected inside the area of interest on the reference cross-section and histograms of grayness distribution of the individual components are obtained. All histograms are normalized by their area, i.e. by number of pixels. The histograms of all individual components are transformed to general scale. Histogram of the area of interest of the reference cross-section is approximated by sum of histograms of individual components with some weight coefficients, corresponding to the areas that individual components occupy on this cross-section of the computer tomographic image.

Weight coefficients are obtained by minimization of module of difference between the real histogram of the area of interest of the reference cross-section ($k = 1$) and sum of histograms of individual components:

$$\left[\sum_{j=1}^M (A_j^1 - b^1 B_j^1 - c^1 C_j^1 - \dots) \right] \rightarrow 0 \quad (3)$$

wherein A_j^1 , B_j^1 , C_j^1 , ... are vectors of values of histograms, b^1 , c^1 etc are weight coefficients; j is index of grayscale; M is total number of grayscales; upper index "1" corresponds to number of cross-section ($k = 1$).

Weight coefficients b^1 , c^1 etc correspond to areas that individual components occupied on the reference cross-section of the histograms of grayness distribution in the cross-sections of the computer tomographic image.

To reconstruct distribution and concentration of the contrast components along the sample, the procedure described above and including the minimization (3), is applied to all cross-sections inside the area of interest of the computer tomographic image ($k = 1 \dots K$).

In the case of bad convergence of this problem, it is possible to extend the sub-areas containing individual components.

Brief description of the drawings

Fig. 1 shows an example of selecting an area of interest on the cross-section of the computer tomographic image and obtaining the histogram of grayness distribution ;

Fig. 2 shows an example of selecting the sub-areas, containing only one individual material, inside the total area of interest and obtaining the histogram of grayness distribution;

Fig. 3 shows an approximation of histogram using Gaussians as probability density functions;

Fig. 4 shows an example of profile for mixture of three different materials.

Detailed description of the invention

According to the first embodiment of the invention a porous sample (artificial sample, consisting of sand grains and liquid glass as cement material) is scanned with X-ray and a computer tomographic image of the sample is obtained. Then an area of interest inside of this computer tomographic image is selected and a first cross-section of the computer tomographic image (let us call it as reference cross-section and assign a number $k = 1$) is defined. Under an area of interest we understand a sub-area of 3D X-ray computer tomographic image which is selected for detailed analysis. This area can be selected because it includes some specific features (microfractures, defect or specific inclusion) or as typical volume of image to reduce simulation time (if initial 3D X-ray image is too large for analysis).

A histogram of grayness distribution inside the area of interest of the reference cross-section is obtained using special program (for, example, ImageJ – <http://rsbweb.nih.gov/ij/>), see Fig. 1.

The number of the components is defined as the number of peaks on the histogram of grayness distribution inside the area of interest on the reference cross-section. The histogram $I_i^1(z)$ of grayness distribution for each component inside reference cross-section ($k = 1$) is approximated by normal distribution (Gaussian function):

$$I_i^1(z) = A_i^1 \exp \left[- \left(\frac{z - B_i^1}{C_i^1} \right)^2 \right]$$

wherein i is index of a component; I is “intensity” (total number of pixels) of grayness z ; A_i^1 , B_i^1 , C_i^1 are adjustable parameters; upper index “1” corresponds to number of cross-section ($k = 1$).

Example of hystogram of selected individual material is given in Fig. 2.

Adjustable parameters for all components are crudely estimated from the histogram of grayness distribution inside the area of interest. Accurate estimation of adjustable parameters for the components is made by minimization of module of difference between the histogram of grayness distribution inside the area of interest of the reference cross-section and sum of normal distributions, corresponding to individual components

$$\sum_{j=1}^M \left[H^1(z_j) - \sum_{i=1}^N A_i^1 \exp \left(- \left(\frac{z_j - B_i^1}{C_i^1} \right)^2 \right) \right] \rightarrow 0 \quad (1)$$

wherein j is index of grayscale; M is total number of grayscales; N is total number of different components. Approximation result is shown on Fig.3.

The fraction a_i^1 of the individual components inside the reference cross-section of the computer tomographic image is calculated as:

$$a_i^1 = \int A_i^1 \exp \left[- \left(\frac{z - B_i^1}{C_i^1} \right)^2 \right] dz \quad (2)$$

Obtained parameters of Gaussians A_i^1 , B_i^1 , C_i^1 of the reference cross-section are used as initial parameters for minimization of module of difference between the real histogram of grayness distribution and it's approximation by sum of normal distributions (1) for next cross-section of the computer tomographic image ($k = 2$) and so an.

To reconstruct the distribution and concentration of the contrast components along the sample the minimization of module of difference between the real histogram of grayness distribution and its approximation by sum of normal distributions (1) and the expression (2) are applied to all cross-sections inside the area of interest of the computer tomographic image ($k = 1 \dots K$).

Typical example of reconstructed profile for mixture of three different components is shown on Fig.4.

According to the second embodiment of the invention a porous sample (artificial sample, consisting of sand grains and liquid glass as cement material) is scanned with X-ray and a computer tomographic image of the sample is obtained.

Then an area of interest inside of this computer tomographic image is selected and a first cross-section of the computer tomographic image (let us call it as reference cross-section and assign a number $k = 1$) is defined. A histogram of grayness distribution inside the area of interest of the reference cross-section is obtained using special program (for, example, ImageJ – <http://rsbweb.nih.gov/ij/>), see Fig. 1.

Then, the sub-areas each containing only one individual component are selected inside the area of interest on the reference cross-section and histograms of grayness distribution of the individual components are obtained, see Fig.2. All histograms are normalized by their area, i.e. by number of pixels. This way amount of pixels in every range of histogram must be divided by amount of all selected pixels. The histograms of all individual components are transformed to general scale, for example, to scale of histogram of total area of interest. Histogram of the area of interest of the reference cross-section is approximated by sum of histograms of individual components with some weight coefficients, corresponding to the areas that

individual components occupy on this cross-section of the computer tomographic image.

Weight coefficients are obtained by minimization of module of difference between the real histogram of the area of interest of reference cross-section ($k = 1$) and sum of histograms of individual components:

$$\left[\sum_{j=1}^M \left(A_j^1 - b^1 B_j^1 - c^1 C_j^1 - \dots \right) \right] \rightarrow 0 \quad (3)$$

wherein A_j^1 , B_j^1 , C_j^1 , ... are vectors of values of histograms, b^1 , c^1 etc are weight coefficients; j is index of grayscale; M is total number of grayscales; upper index "1" corresponds to number of cross-section ($k = 1$).

Weight coefficients b^1 , c^1 etc correspond to areas that individual components occupied on the reference cross-section of the X-ray image.

To reconstruct distribution and concentration of the contrast components along the sample, the procedure described above and including the minimization (3), is applied to all cross-sections inside area of interest of the computer tomographic image ($k = 1 \dots K$).

In the case of bad convergence of this problem, it is possible to extend the sub-areas containing individual components or check that all principle materials are taken into account.

CLAIMS

1. A method for determination of spatial distribution and concentration of contrast components in a porous or / and heterogeneous sample comprising the following steps:

- scanning the sample with X-ray,
- obtaining a computer tomographic image of the sample,
- defining an area of interest inside the obtained computer tomographic image,
- defining a reference cross-section of the obtained computer tomographic image ,
- obtaining histograms of grayness distribution in the cross-sections of the computer tomographic image,
- determining spatial distribution and concentration of contrast components along the sample by analyzing histograms of grayness distribution in the cross-sections of the computer tomographic image starting with a histogram of grayness distribution in the reference cross-section.

2. A method of claim 1 wherein a step of analyzing histograms of grayness distribution in the cross-sections of the computer tomographic image comprises the following:

- defining the number of the components as the number of peaks on the histogram of grayness distribution inside the area of interest of the reference cross-section,
- approximating the histogram $I_i^l(z)$ of grayness distribution for each component inside the reference cross-section by normal distribution (Gaussian function):

$$I_i^1(z) = A_i^1 \exp \left[- \left(\frac{z - B_i^1}{C_i^1} \right)^2 \right]$$

wherein

i is an index of a component;

I is “intensity” (total number of pixels) of grayness z ;

A_i^1 , B_i^1 , C_i^1 are adjustable parameters corresponding to the reference cross-section;

upper index “1” corresponds to the reference cross-section,

- crudely estimating adjustable parameters for all components from the histogram of grayness distribution inside the area of interest of the reference cross-section,

- accurately estimating adjustable parameters for the components by minimization of module of difference between the histogram of grayness distribution inside the area of interest of the reference cross-section and sum of normal distributions corresponding to individual components

$$\sum_{j=1}^M \left[H^1(z_j) - \sum_{i=1}^N A_i^1 \exp \left(- \left(\frac{z_j - B_i^1}{C_i^1} \right)^2 \right) \right] \rightarrow 0$$

wherein

j is index of grayscale;

M is total number of grayscales;

N is total number of different components,

- using obtained parameters of Gaussians A_i^1 , B_i^1 , C_i^1 as initial parameters for minimization of module of difference between the histogram of grayness distribution and it's approximation by sum of normal distributions for the next cross-section of the computer tomographic image,

- applying previous step to all cross-sections inside the area of interest of the computer tomographic image,
- defining the fraction of the individual components inside each cross section k by integration of individual Gaussians:

$$a_i^k = \int A_i^k \exp \left[- \left(\frac{z - B_i^k}{C_i^k} \right)^2 \right] dz,$$

wherein $k = 1 \dots K$ is the number of cross-section.

3. The method of claim 1 wherein a step of analyzing grayness distribution in the cross-section of the computer tomographic image comprises the following:

- selecting the sub-areas inside the area of interest on the reference cross-section, each containing only one individual component,
- obtaining histograms of grayness distribution of the individual components,
- normalizing all histograms by their area,
- transforming the histograms of all individual components to general scale,
- approximating the histogram of the area of interest on the reference cross-section by sum of histograms of individual components with the weight coefficients, corresponding to the areas occupied by the individual components on this cross-section of the computer tomographic image,
- defining weight coefficients by minimization of module of difference between the histogram of the area of interest on the reference cross-section and sum of histograms of individual components:

$$\left[\sum_{j=1}^M \left(A_j^1 - b^1 B_j^1 - c^1 C_j^1 - \dots \right) \right] \rightarrow 0$$

wherein

$A_j^1, B_j^1, C_j^1, \dots$ are vectors of values of histograms,

$b^1, c^1, \dots$ are weight coefficients;

j is index of grayscale;

M is total number of grayscales;

- applying previous step to all cross-sections inside the area of interest of computer tomographic image.

4. Method of claim 3 wherein the sub-areas containing individual components are expanded.

1/4

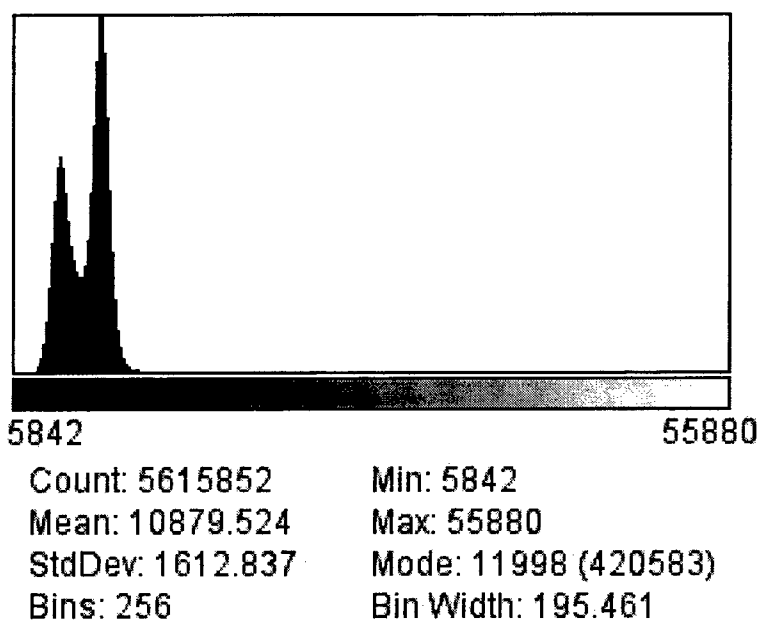
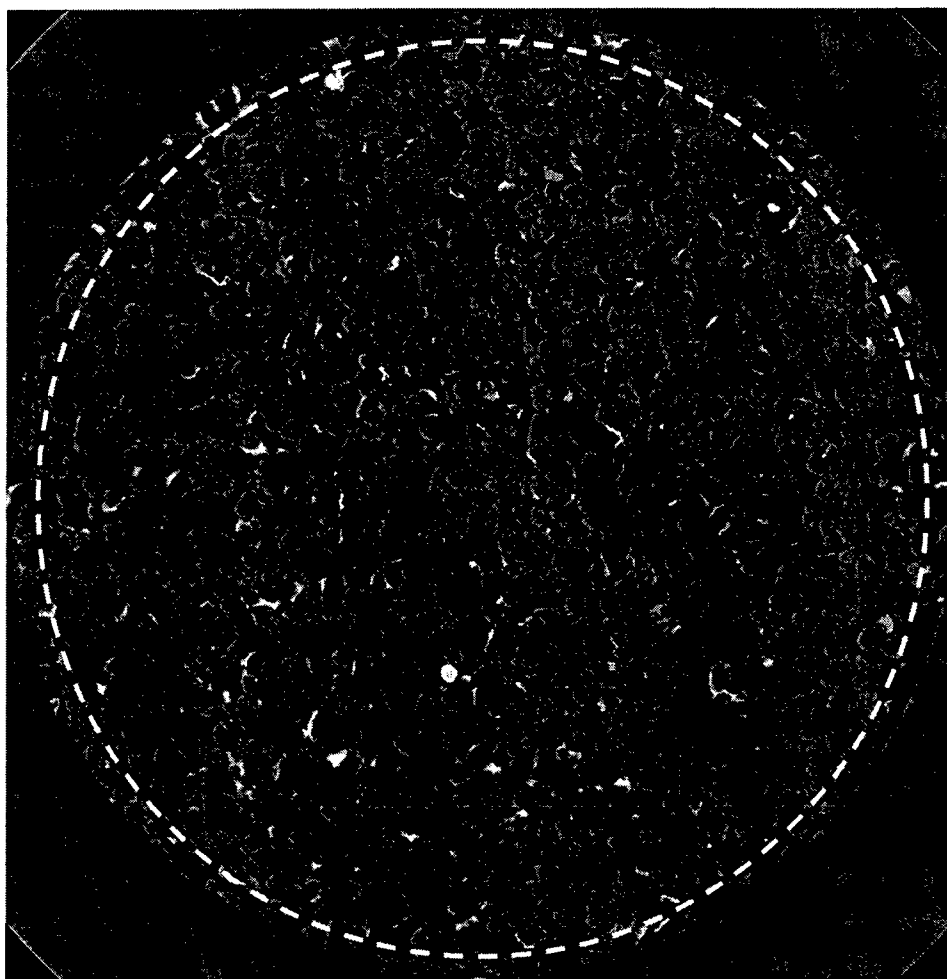


Fig. 1

ЗАМЕНЯЮЩИЙ ЛИСТ

2/4

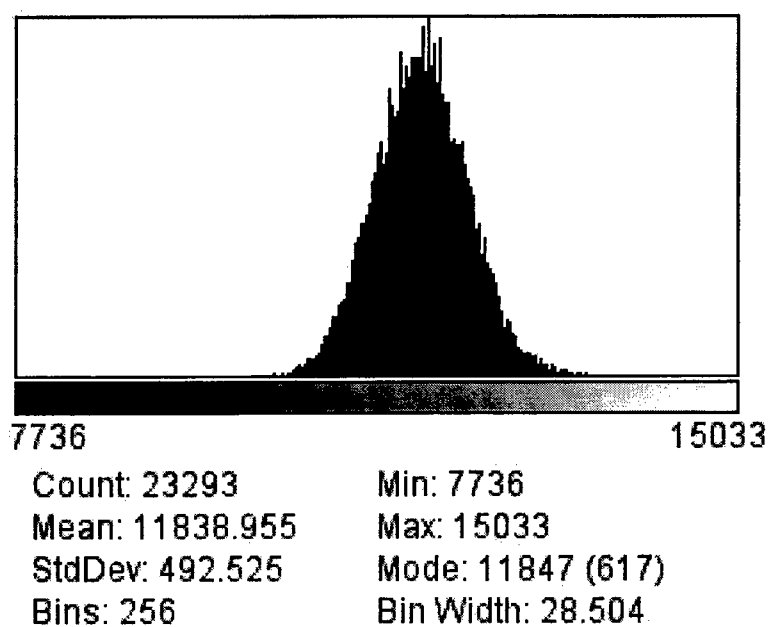
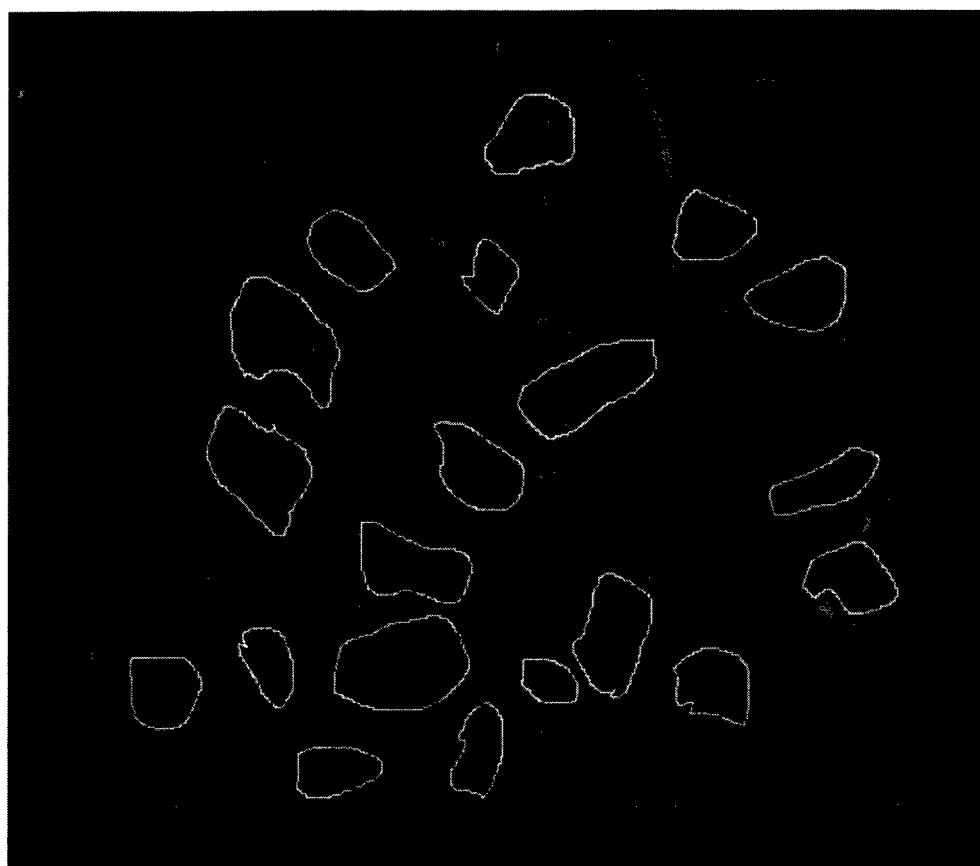


Fig. 2

ЗАМЕНЯЮЩИЙ ЛИСТ

3/4

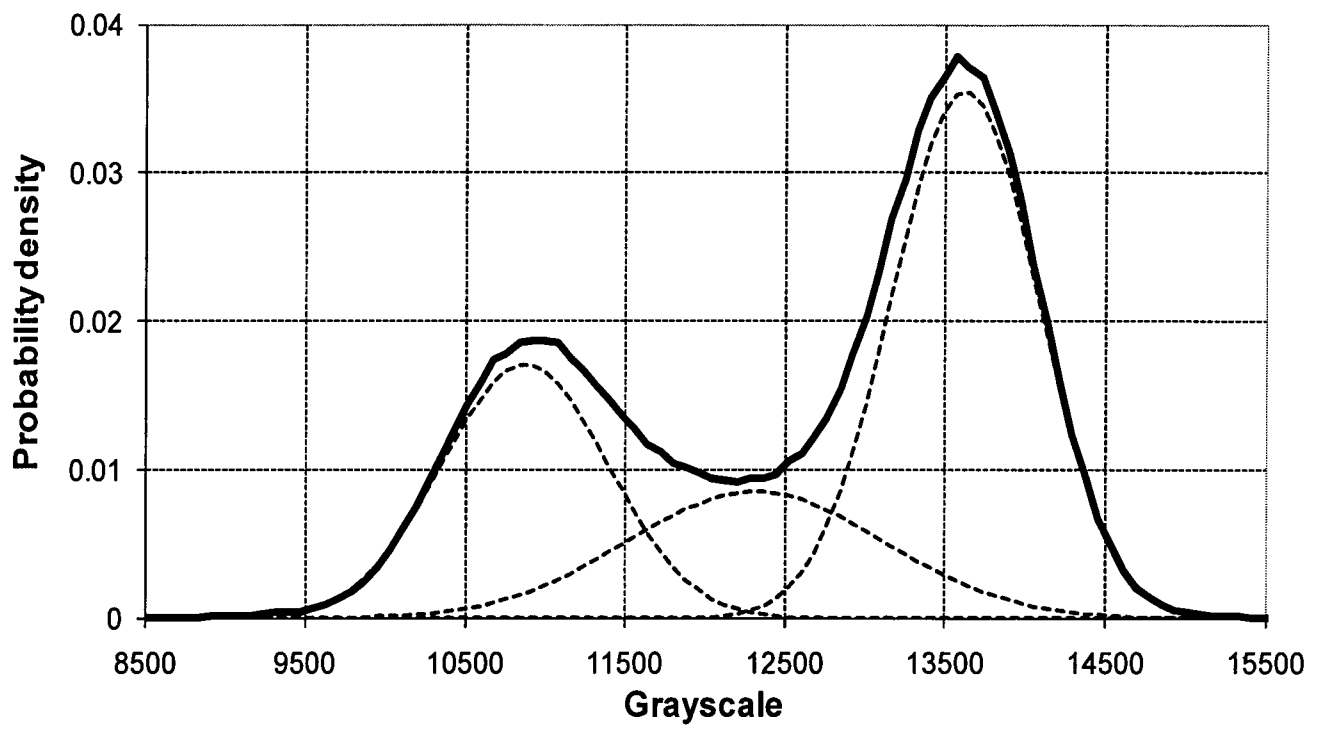


Fig. 3

4/4

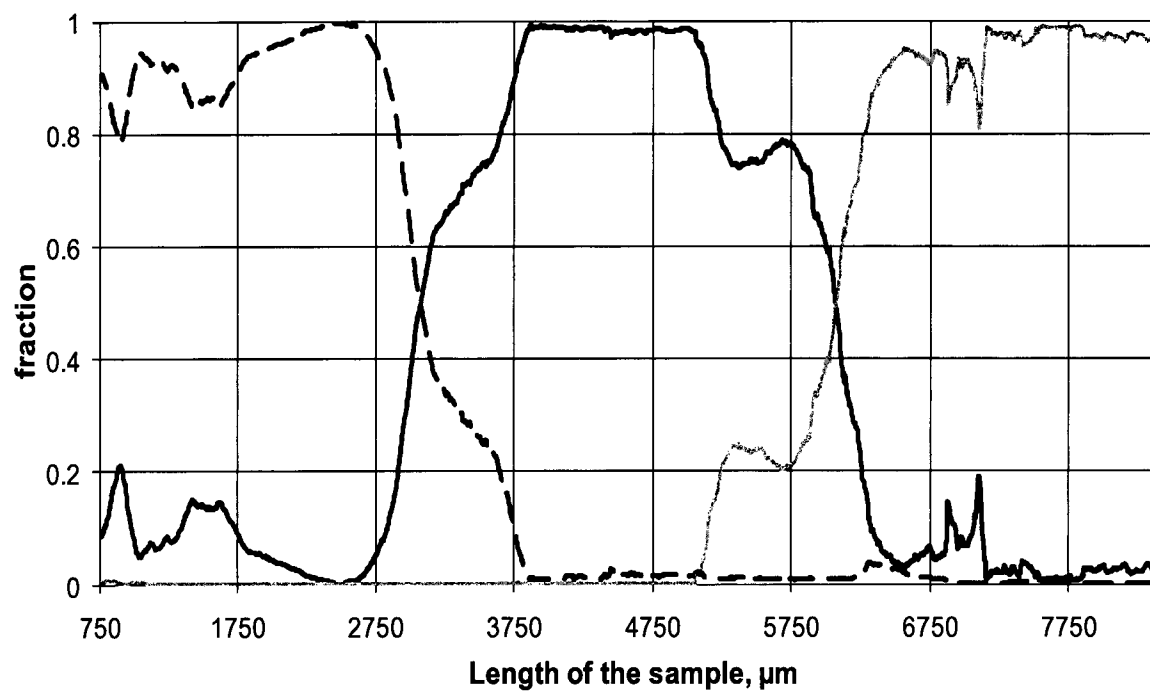


Fig. 4

INTERNATIONAL SEARCH REPORT

International application No.

PCT/RU 2011/000378

A. CLASSIFICATION OF SUBJECT MATTER <i>G01N 23/083 (2006.01)</i>				
According to International Patent Classification (IPC) or to both national classification and IPC				
B. FIELDS SEARCHED				
Minimum documentation searched (classification system followed by classification symbols)				
G01N 1/18, 15/02, 15/08, 21/31, 21/49, 23/00-23/083, G06F 17/18				
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched				
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)				
RUPAT, RUABRU, RUPAT-OLD, RUABU1, Esp@cenet, PAJ, USPTO DB				
C. DOCUMENTS CONSIDERED TO BE RELEVANT				
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
A	US 2005/0010106 A1 (IMAGING THERAPEUTICS INC.) 13.01.2005	1-4		
A	RU 84548 U1 (OBSCHESTVO S OGRANICHENNOI OTVETSTVENNOSTIYU "LABORATORIYA OPTIKO-ELEKTRONNYKH PRIBOROV") 10.07.2009	1-4		
A	US 6738144 B1 (UNIVERSITY OF CENTRAL FLORIDA) 18.05.2004	1-4		
A	US 7319739 B2 (SIEMENS AKTIENGESELLSCHAFT) 15.01.2008	1-4		
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.				
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Date of the actual completion of the international search 20 January 2012 (20.01.2012)		Date of mailing of the international search report 01 March 2012 (01.03.2012)		
Name and mailing address of the ISA/ FIPS Russia, 123995, Moscow, G-59, GSP-5, Berezhkovskaya nab., 30-1		Authorized officer A. Samatadze		
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