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New X-ray testing methods of aerosol products for industrial radiography

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ABSTRACT

An amount of product in e.g. an aerosol canister is not difficult to estimate by weighing a filled can and subtracting the tare of packaging. In this way, we can obtain the net weight of the ingredients present in the can. Although, this does not indicate the volumetric content. Therefore, in the paper, the fundamental (the weight method and given by FEICA) and new methods (given by authors) related to the determination of the volumetric content of canister filled with aeorosol products are presented. The new methods are based on direct digital radiography (DR) using X-ray radiation. For the needs of new methods, the X-ray CCD-DR imaging system was built and developed in our Laboratory in Department of Radiation and Vibration at the Central Office of Measures. For comparison purposes, with regard to the volumetric content, a lot of metal cans of capacities 140, 185, 450, 700 ml were inspected. In future, computed tomography (CT) for industrial radiography in our laboratory will be used. Currently, an algorithm for CT is being tested. It will give us possibility for very precise measurements to determine volumetric content of examined canisters.

1. Introduction

Among other things quality is important for a business. Quality of goods allow to provide customer satisfaction and diminish the danger and cost of changing wrong products. Particularly, the inspection of products should be done very accurately before it is delivered to customer. Thus, for example, the content of the given product should be the same as on the label is written. It concerns, in particular, a nominal value of volume given by manufacturer on the can of aerosol product. In connection with this, the proper non-destructive testing method for determination of volume has to be used.

At present, there are some X-ray imaging techniques which has turned out to be one of the most valuable instruments in inspection of product content. Nowadays, different kinds of radiation-sensitive films and detectors do not require development chemicals to produce images, so-called dry processes, are increasingly used. These techniques need computers to be applied. Hence, these techniques are called: computed radiography (CR) or direct digital radiography (DR) [1,2]. The “classic” film in its light-tight cassette (plastic or paper) is usually placed just behind the inspected object and ionizing radiation is switched on for some time (exposure time) after which the film is taken away and processed photographically, i.e. developed, fixed, washed and dried. In direct digital radiography (DR), a coherent image is formed directly by means of a computerized development system. These two methods have a negative image. Areas where the absorption is less allow more ionizing radiation to be transmitted. Although, there is a difference in the formation of images between the two mentioned techniques, the interpretation of images can be done in exactly the same way.

The above-mentioned techniques of radiography are usually used in preliminary medical diagnosis and simple security inspection [3]. Additionally, it is worth to note, there is also increasing interest in applications for industrial radiography [2,4].

The major task of digital radiography is rebuilding of the physical parameters that terminate technical features of the monitored objects being inspected. This is ordinarily performed by restoration of the spatial configuration, engaged small specific aspects and defects of the image, and resolving constituive components and dimension (thickness, volume) [5,6].

One of such most important structure parameter is the effective atomic number Z_{eff} [5–8]. In fact, this quantity can give an initial appraisal of the chemical composition of the material. A large value of Z_{eff} ($Z_{eff} \geq 20$) corresponds to inorganic compounds and metals. Whilst, a small value of Z_{eff} ($Z_{eff} \leq 10$) indicates organic substances. Thus, the effective atomic number can have a decisive importance for many applications e.g., for radioisotope monitoring, cross-section studies of absorption, testing of multi-component, heterogeneous substances.

Therefore, the main goal of the paper is to present an X-ray CCD-DR imaging system built in our laboratory and concentrate on novel

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methods for volumetric determination of the inspected canisters with aerosol products by using X-ray radiation for industrial radiography.

2. Experimental details

The most versatile way to determine volumes of the inspected products are tests with using X-rays. These tests are reliable and provide results with high accuracy but require special X-ray machines.

Thus, such measurement system was built in the Laboratory of Ionizing Radiation and Colour Standards in the Department Radiation and Vibration at the Central Office of Measures. An X-ray picture of the end aerosol product gives a specific look inside of the container without any mechanical damage and provides clear results concerning the assessment of the content. This method can be destructive or non-destructive, e.g. by comparing the quality of product to the previously prepared standards. This method can be visualized in respect of single photographs or by placing a few cans next to each other and taking of the photo. The experimental setup of the mentioned system is presented in Section 2.1.

The weight method and methods using X-ray source are described in Section 3.

2.1. The X-ray CCD-DR imaging system

The costs of purchase of system for industrial radiography are very high [9,10]. The systems of medical radiography are not much cheaper either. Our laboratory in the Radiation and Vibration Department at the Central Office of Measures maintains primary standards for the determination of the quantity air kerma in X-radiation with generating potentials in the range from 10 kV to 250 kV and primary standards for the determination of the quantities air kerma and absorbed dose to water in ^{60}Co gamma-radiation, and air kerma in ^{137}Cs gamma-radiation. In connection with above, the laboratory has required ionizing radiation sources. Therefore, in our laboratory, the proposed X-ray CCD-DR imaging system shown in Fig. 1 was built and developed.

This X-ray CCD-DR imaging system consists of:

1. An X-ray tube with equipment (high voltage generator, control panel etc.).
2. A canister as an inspected object.
3. A rotary table where the inspected object is placed.

   It allows to take photographs for computed tomography (CT) [11].
4. A fluorescent screen plate applied to receive the X-ray irradiation and then produce the visible light image.
5. A mirror with fullfilled requirements such as coated film with high reflection coefficient (95%).
6. The Nikon D5200 digital camera with CCD (of Nikon Company) used to record the X-ray image formed on the surface of the mirror.
7. A table where the image system is set up.
8. A light-tight housing.
9. A personal computer used to acquire, analyse data and X-ray image process.

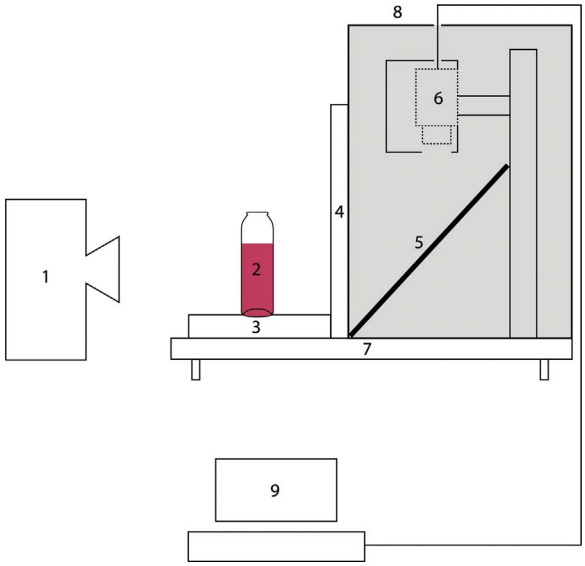

Fig. 1. Schematic diagram of the proposed X-ray CCD-DR imaging system: 1—X-ray tube with equipment (high voltage generator, control panel etc.), 2—inspected object, 3—rotated table, 4—fluorescent screen, 5—mirror, 6—digital camera, 7—table, 8—light-tight housing, 9—personal computer.

In particular, the main physical factors of the X-ray CCD imaging system are listed below:

1. object distance from the X-ray tube: 1000 mm;.
2. focal lengths of the X-ray tube: 3 mm and 5 mm;.
3. the X-ray tube voltage used for cans: 125 kV;.
4. voltage range of the X-ray tube applied for ionization chambers: 50–150 kV;.
5. the X-ray tube current used for cans: 10 mA;.
6. current range of the X-ray tube applied for ionization chambers: 5–15 mA.
7. inherent filtration of the X-ray tube: Al 4 mm;.
8. detector bin size: 300 mm x 400 mm.
9. focus mode of the digital camera: automatic.

The proposed X-ray CCD-DR system was built on the basis of some ideas given among other things in [12].

2.2. The preprocessing method

Before the direct digital radiography (DR) image can be used for analysis, the original DR images without any correction will be processed by personal computer. Procedures of the preprocessing method used in this paper and based on the method proposed in [12] are as follows:

1. Acquirement of the original DR image.
2. Performance of flat-field correction.
3. Performance of image gamma correction.
4. Using of median filter.
5. Carring out image contrast enhancement.

The acquired direct digital radiography images are predominantly characterized by small contrast and overexposure, which makes them tough to preprocess, such as image denoising and contrast enhancement. In the past, some multiscale image contrast enhancement techniques, such as multiscale image contrast amplification (MUSICA) algorithm [13] and wavelet-based methods [14], have proved that they are effective for modifing X-ray imaging quality. Hence, in order to get results sufficient for our purpose, we decided to use median filter and Laplace transform [15] followed by flat-field and gamma corrections. In our work, the chosen algorithm for image contrast enhancement supported good performance in representing the image noticeable features such as curves, lines, edges, and contours.

2.3. The validation of the X-ray CCD-DR imaging system

For the validity of the experimental setup, in according to the procedures used for medical devices (two medical phantoms: for fluoroscopy and digital radiography) [1], the CCD-DR imaging system was tested. The results are shown in Fig. 2 and confirm high quality

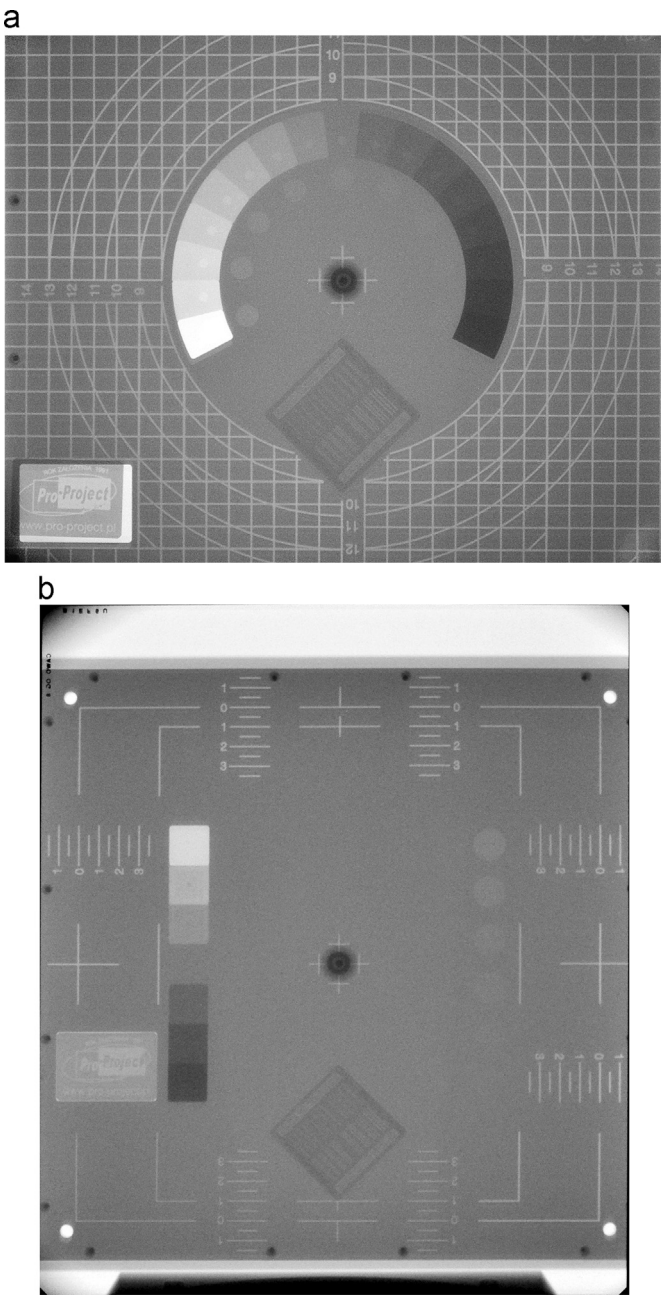

Fig. 2. The X-ray images of phantoms for (a) fluoroscopy and (b) digital radiography, respectively.

images obtained by the proposed imaging system.

The above described experimental setup was used for the volume determination of test objects. Information on the test objects is given in Section 2.4.

2.4. Test objects

Test objects were various metal cans of different capacities (140, 185, 450, 700 ml), with substances of different phases (in the form of aerosols, liquid and foam), density and composition. A lot of canisters (above 100 cans) using methods presented in Section 3 have been tested.

Additionally, in respect of volume, certain ionization chambers were also examined.

3. Methods for the volume determination of aerosol products

In this section, the fundamental (the weight method and given by FEICA) and new methods (given by authors) of the volume determination of canister filled with aeorosol products are described in detail.

3.1. Methods without using X-ray

3.1.1. The weight reference method

The amount of product in e.g. the mass of a polyurethane foam canister is easily assessed by weighing of the filled canister and subtracting the tare of the packaging. This gives the net mass of the ingredients in the can. On the basis of the determined mass and the density for each ingredient included in the investigated canister, we can calculate the volume of all ingredients which are the composition of the tested can. Therefore, this weight test method was used as a reference method in the inspection of metal canisters.

Many other methods of volume determination one can find in [16].

3.2. Methods with using X-ray

3.2.1. The FEICAOne Component Foam (OCF) testing method

The document [17] describes how to determine the real volume of liquid ingredients in a metal canister. Calibration canisters are prepared by filling canisters of the same nominal volume as the test canister with a known quantity of water (not pressurized). The shape of both calibration cans (diameter and bowing at the bottom) must be identical to the test canisters. The quantity of water is precisely measured by weighing and the water temperature should be 23 °C ± 3 °C. The tap water quality is sufficient. The content of the calibration canisters shall depend on the nominal volumetric content of the canister to be tested [1].

An X-ray image is taken of each test can with calibration canister 1 on the one side, and calibration canister 2 on the other side of the test can. If necessary, more test canisters can be placed between the two calibration canisters. Care should be taken to ensure that the canisters are standing on the same surface, which should be in a perfectly horizontal position. The image should be taken so that the X-ray tube is more or less at the same height as the expected liquid level of the test can, i.e. between the two liquid levels of the calibration canisters. The X-ray image can be fixed using a variety of techniques, such as photographic film or digital imaging. The result should be something like in Fig. 3 [1].

The proper filled level of the test canister is calculated by

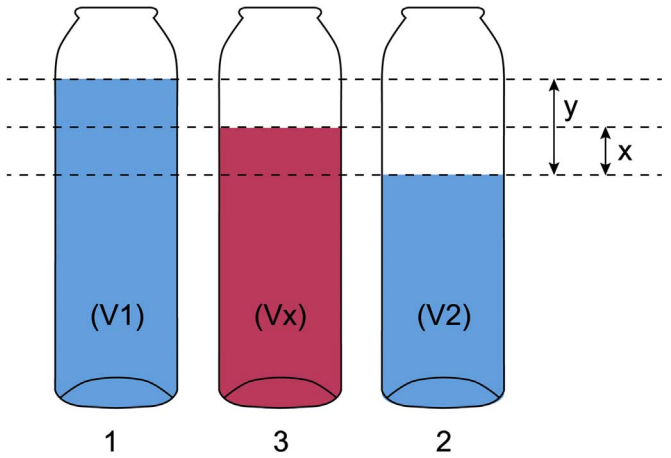

Fig. 3. The graphical representation of measurement methods. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

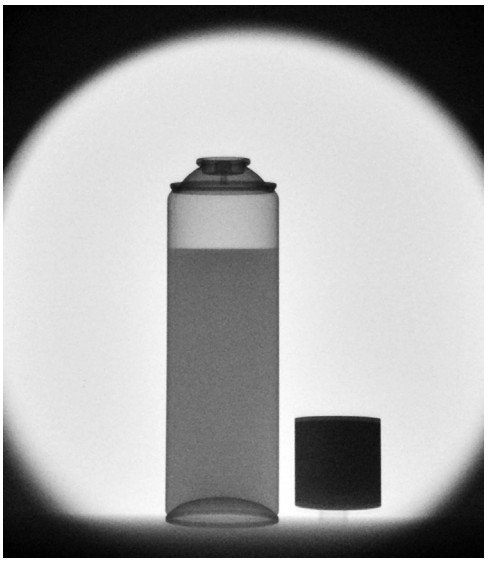

Fig. 4. The X-ray photographic image of a calibrated steel roll and canister.

interpolation, according to the following equation [17]:

$$V_x = V_2 + \frac{x}{y}\cdot(V_1 - V_2) \tag{1}$$

where x and y are the distances measured from the X-ray image using the calibrated ruler. V_1 calibration canister 1 and V_2 calibration canister 2. As the larger the scale of the X-ray image, the more accurate x and y can be measured. Note that in cases where the filled level of the test canister is less than that of calibration canister 2, distance x should bear a negative sign [17].

3.2.2. The first new testing method

The method discussed above is very simple in use, provided that an empty canister identical to the tested one is available.

In order to avoid the fulfilled above-mentioned condition, we figured the new method out. Hence, it can be noticed, that a canister with aerosol product consists of two interpenetrating solids: a roll and the slice of a sphere. It is shown in Figs. 4 and 5.

Thus, the volume of a spray (liquid, foam) in the canister is expressed as the difference between the roll and the slice of the sphere:

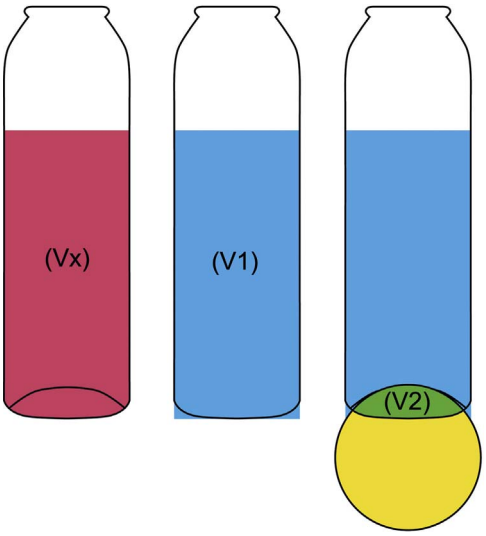

Fig. 5. The graphical representation of the first new measurement method. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

$$V_x = V_1 - V_2 = (\pi\cdot R^2\cdot H) - \left(\frac{\pi\cdot h}{6}\cdot(3r^2 + h^2)\right) \tag{2}$$

where R is radius of the roll, H is the height of the roll, r is the radius of the slice of the sphere, h is the height of the slice of the sphere.

In the internet, there are some useful graphical programs with many tools for image processing and analysis for free. Authors use the GIMP (GNU Image Manipulation Program). It is a free and open-source raster graphics editor [18,19] used for image retouching and editing, free-form drawing, resizing, cropping, photo-montages, converting between different image formats, and more specialized tasks. Particularly, the GIMP contains tools such as filters, lines and measure, what is shown in Fig. 6, which can be used to measure the needed values found in Eq. (2).

There is an object of known physical dimensions: height, width, e.g. a calibrated steel roll (see Fig. 4 to the right side of the canister) with a known diameter and height. And it is an X-ray image of this object (the calibrated steel roll). It can be noticed that the pixel size is easily converted into size in millimetres:

$$k = \frac{a}{b} \tag{3}$$

where k is the calibration coefficient for the image, and a is the averaged value of the width and the height of the reference object in mm, b is the mean value of the width and the height of the reference object in pixels. Knowing the values of R, H, r, h and k, the volume of the spray can be calculated. This volume can be expressed in mm^3 or ml.

The scrutiny image analysis was performed by using preprocessing method presented in Section 2.2. For image contrast enhancement, the "Laplace filter" with the following mask was applied:

$\begin{bmatrix} -1 & -1 & 0 \\ -1 & 3 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ with normalize option and three colour channels: red, green, blue.

3.2.3. The second new testing method

The two methods described in Sections 3.1.1 and 3.2.1 are required to perform the manual measurement by operator. It may cause errors. Moreover, these methods do not take into account the prevalence of the meniscus, etc. The first author has developed a new method, which eliminates the above errors and this method can be mostly automated. The first step is pre-treatment of X-ray image by using preprocessing method given in Section 2.2. In the next step, the probe of aerosol is selected in X-ray image by an operator. Complete area of an aerosol is filled by colour e.g. red. The following step is to scan X-ray image along its height. The step scan is 1 pixel.

During the scan, marked pixels are found and counted. There are possible two situations:

- pixels in line are still, in effect, the volume of a roll V_i is calculated;
- pixels in line are not still, in effect, the volume of a ring V_i is calculated.

The individual volumes V_i are summed up what is shown in Fig. 7 and volume of aerosol is expressed by formula:

$$V_x = \sum_{i=0}^{N} V_i \tag{4}$$

In order to implement the method shown, a computer program was written in Delphi language. Currently, authors select parameters of exposure and filters for processing of X-ray images. The scrutiny image analysis was performed by using preprocessing method described in Section 2.2.

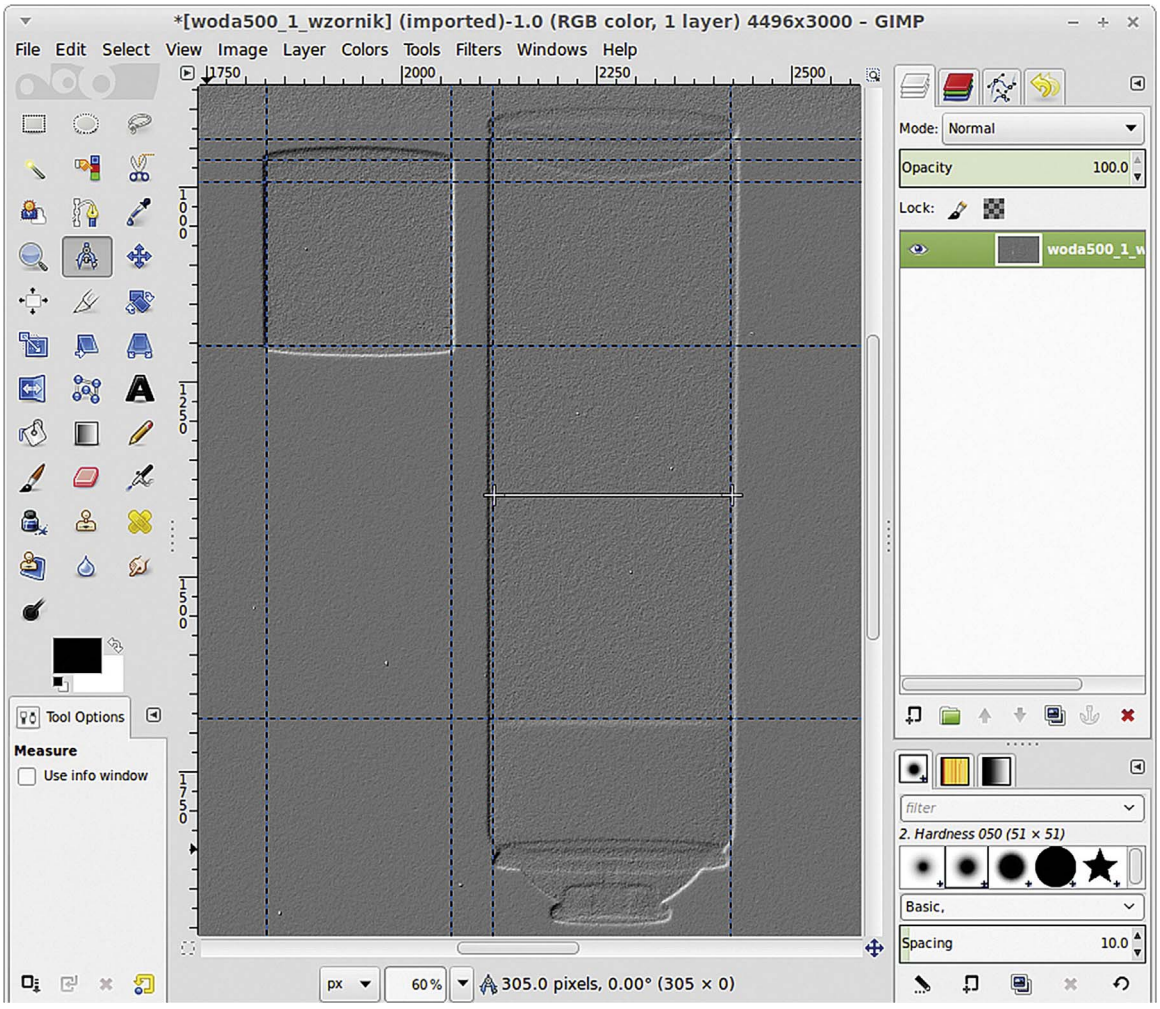

Fig. 6. The screenshot of GIMP software with processed X-ray photographic image from Fig. 4.

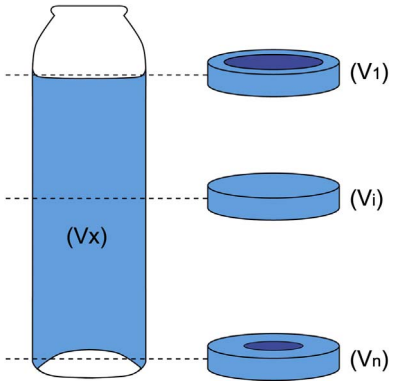

Fig. 7. The graphical representation of the second new testing method. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

4. Comparison of methods and other experimental results

4.1. Comparison of methods

The temperature of the volumetric measurement for each method was the same, $T = 20$ °C. Results of the volumetric measurements taken by using the above mentioned methods are given in Tables 1–3.

On the basis of results given in Table 3, we can see there is no significant difference between values obtained by two former presented methods for volume 140 and 700 ml. In these two methods, meniscus was not taken into account in volumetric calculations. In the case of the method no. 3, the meniscus was taken into account, it seems that the volumetric values obtained by the third method are much more probable. Currently, there are works on the elaboration of the third new testing method using computed tomography. Particularly, an

Table 1
The values of volumes V_x determined by FEICA [17] (the method no. 2 given in Section 3.2.1), errors (V_{ref}-V_x) and relative errors. V_{ref}-the reference volume determined by the weight reference method (method no. 1 given in Section 3.1.1).

V_{ref} (ml)	V_1 (ml)	V_2 (ml)	V_x (ml)	V_{ref}-V_x (ml)	V_{ref}/V_x (%)
139.940	149.907	129.967	139.937	0.003	−0.002
185.005	199.936	169.944	185.404	−0.399	0.215
449.931	499.957	399.986	450.656	−0.725	0.161
699.960	749.980	649.940	699.960	0.000	0.000

Table 2
The values of volumes V_x determined by the first new testing method (the method no. 3 described in Section 3.2.2), errors (V_{ref}-V_x) and relative errors. V_{ref} the reference volume determined by the weight reference method (the method no. 1 given in Section 3.1.1).

V_{ref} (ml)	V_1 (ml)	V_2 (ml)	V_x (ml)	V_{ref}-V_x (ml)	V_{ref}/V_x (%)
139.940	148.291	8.666	139.625	0.315	−0.226
185.005	192.126	6.443	185.683	−0.678	0.365
449.931	466.355	14.760	451.595	−1.664	0.368
699.960	709.746	12.105	697.641	2.319	−0.332

Table 3
The values of volumes determined by three methods (the method no. 1—the weight reference method, the method no. 2—the FEICA OFC method, the method no. 3—the first new testing method).

Method no.	140 (ml)	185 (ml)	450 (ml)	700 (ml)
1	139.940	185.005	449.931	699.960
2	139.937	185.404	450.656	699.960
3	139.625	185.683	451.595	697.641

algorithm of the new second and the new third testing methods is being tested. Therefore, the results for the method no. 4 (the method described in Section 3.2.3) have not been shown yet.

4.2. Other experimental results

In dosimetry, volume of ionization chambers as one of many parameters plays very important role in determination of dose rate and/or kerma in the field of γ and X-ray radiation. Hence, it is worth of emphasizing that proposed CCD-DR imaging system was also used for volume calculation of an ionization chambers. For ionization chamber of volume 4.11 cm^3 we obtained the difference between our measurement and the reference value. The volumes difference and the uncertainty measurement were equal to 0.0055 cm^3, 0.2%, respectively. The reference value was usually determined by means of coordinate measuring machines. Whereas, for determination of the ionization chamber volume, the scrutiny analysis of obtained X-ray photograhic images of chambers was performed by the proffesional computer graphic using GIMP software.

It is worth of emhasizing that for ionization chambers before gamma corrections for each ionization chamber several photographs were taken. On the basis of series of experiments with various combination of operations performed on the above mentioned photographs, the following procedures were applied:

(1) addition of two photographs taken for 50 V and 75 V of X-ray tube voltage with 50% coverage;
(2) multiplication of image obtained in point (1) and of photograph taken at the 150 V of X-ray tube with 60% coverage;
(3) using a sharpening mask of the image obtained in point (2).

After gamma correction (but before using median filter) for better detection of edges the following procedures were used: positive radial distorsion matrix, selective Gaussian blur and image thresholding with appropriate physical factors.

5. Conclusions and discussion

Method No. 1 and No. 2 do not take meniscus into account in volumetric calculations. Therefore, there are the clear difference between the volume results given by method No. 3 and the two former methods. In connection with this, it seems that the volumetric values obtained by methods given by authors of this work are much more probable. There are some works on developing of the newest method (the third new testing method) with computed tomography in order to determine volume of the canister very accurately. We proved also that our novel methods can be used not only for industrial radiography but for precise volumetric measurements of ionization chambers of cyllindrical shapes with volume not less than 4 cm^3. On the contrary, results of ionization chamber volumes less than 1 cm^3, one can find in [20–22].

For cans the procedures mentioned in Section 2.2 were sufficient. But for ionization chambers where each feature plays salient role during scutiny analysis of the image, additional operations mentioned in Section 4.2 were inevitable for precise determination of the chamber ionization volume.

Thus, it is known that ionization chambers are important detectors in radiological protection and medicine applications. More precise determination of chambers parameters have to ensure much better results in metrology and dosimetry applications.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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