

A Flowmeter for Measurements of Very Small Gas Flows

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Received: 15 December 2003 /Accepted: 14 February 2004 /Published: 20 February 2004

Abstract: The paper presents description of a flow meter for measurements of very small gas flows (some or several ml/min). Low elementary volumes of gas are counted. The elementary volumes are generated as gas bubbles located in a liquid. In the applied method of measurement of the bubble volume, a vertical column is subjected to a homogeneous light beam, next a luminous flux is detected by a set of optical wave-guide detectors. Detection enables to find a bubble and determine its dimensions. Finally, signals from the detectors are changed into electric signals in the measuring converters and they are registered in a computer.

Keywords: gas flow, optical method, optical tomography

1. Introduction

Measurements of amount and flux of the flowing gas are very often done in laboratories and in industry. Gas volume is a function of pressure and temperature, so the measured volume is usually reduced to normal conditions (273.15 K, 0.1013 MPa). Gas volume measurement resolves itself to determination of the tank volume. There are different gases, so different methods and measuring instrument are applied. If amount of the flowing gas is small, energy, velocity and pressure caused by the flowing gas are small, too. Thus, for small amounts of the flowing gas we cannot apply any rotameters, anemometers and vibratory flow meters. Application of constriction flow meters requires relatively large contractions causing suitable large pressure changes and it is not always acceptable in technological processes.

The methods applied for measurements of flows from some to tens m^3/h include measuring equal gas batches and counting how many batches have flowed. Suitable instruments are called flow counters. The Crosslev drum counter (Fig. 1a) is an example of such instrument. In this gas meter, in a tight housing 1 containing water to a controlled level, there is a drum with partitions 2 of special shapes. The chamber shapes and distribution of gas inlets and outlets should provide uniform flow without pulsation. Volume measurement includes determination of equal batches of gas in chambers A, B, C and D. The free surface of water is a limit for a batch of gas, which fills in the rotor chambers and causes its rotation. The pressure drop in the apparatus is 3-5 mm of the column of water. In order to determine the measurement conditions, we measure gas pressure before the gas meter and gas temperature at the gas meter outlet. The drum gas meters are very accurate instruments and they are often applied in laboratories (measuring error 0,5-1 %). They are used for measurements of inert gases, insoluble in the displacing liquid. The range of measurements of the drum gas meters usually does not exceed $50 \text{ m}^3/\text{h}$ [1].

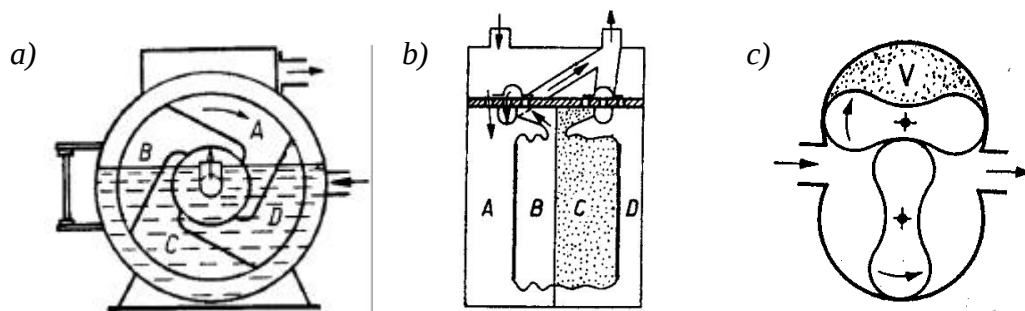


Fig. 1. Flow counters a) Crosslev drum; b) two-bellows; c) rotor

There are also very popular chamber gas meters, especially *bellows gas meters*. In a *two-bellows gas meter* (Fig. 1.b), the internal space is divided into two parts by a stationary baffle, and they are divided into four parts A and B and C and D by two elastic leather bellows. The chambers are alternately filled and emptied. The bellows drive a connecting-rod, joined with their rigid walls. The connecting-rod drives a counter and slides. The gas meters have the measuring range $6+100 \text{ m}^3/\text{h}$. An error of the bellows gas meters is 2-3%.

For industrial measurements of large volumes of the flowing gas, the rotor gas meters are used (Fig.1.c). Swirling oval-concave pistons are driven as a result of a difference in gas pressure between inlet and outlet. The horizontal axes of the pistons are coupled with a gear transmission located outside the counter housing. Each revolution of the pistons causes determination of volume V. Devices of that type are reliable and accurate (accuracy 0.2-0.5) and their measuring range is $10-200 \text{ m}^3/\text{h}$.

If a technological process requires automated measurements and a low pressure drop, and the flow is not constant but varies at time, it is necessary to find other measuring methods. In this paper, the authors propose a solution enabling automated measurements and causing low pressure drops.

2. The flow-meter structure

The flow meter structure is shown in Fig. 2. The gas is delivered to the nozzle 2 mounted at the bottom of the measuring tank 1 containing a liquid. The check valve 3 protects against the liquid overflow and suction in the case of negative pressure in the measuring system. The gas from the nozzle is present in the liquid as bubbles. If a nozzle diameter is suitably chosen, we can obtain bubbles of regular shapes, flowing out at constant time intervals. This is a base for measurements of

the bubbles volume. Those measurements include scanning the tested section and detection of the gas bubble presence. The tested section is subjected to a coherent light beam, emitted by the source 4. When the light beam meets a gas bubble, it divides into some components and, as a consequence, the light beam weakens and the weakening is received by the wave-guide detector 5. In the measuring converter 6, light signals from the detector are changed into an electric signal of TTL standard.

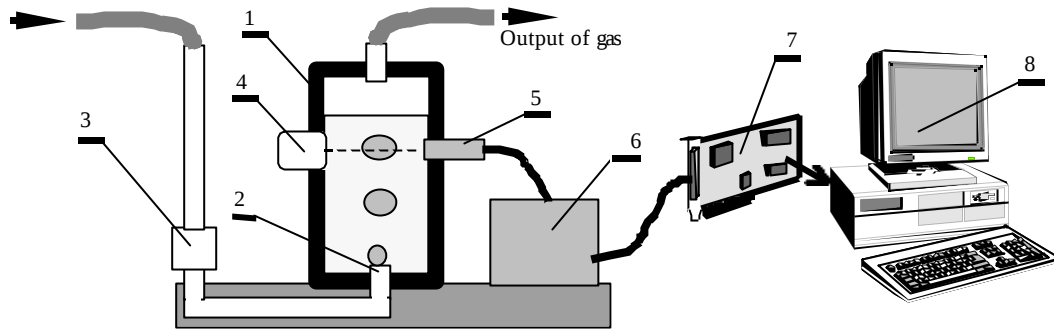


Fig. 2. A flow meter structure

2.1 Idea of the method

In the optical method, a tested section is subjected to a homogeneous light beam and next intensity of the light passing through the liquid with the moving bubbles is detected (Fig.3). The light emitted from its source passes through the column filled with a liquid and is partly absorbed by the it. However, if it meets a bubble, the flux decomposes into some components. As a consequence, the light reaching the detector has a lower intensity. The detectors contain the optical wave-guides placed in the collimation sleeves. Application of the collimation sleeves causes that the opening angle decreases. Since reflection and refraction are dependent on the wave length, it is preferable to use a source of monochromatic light or of a relatively narrow emission spectrum. It is necessary to use an optical system in order to obtain a homogeneous light beam.

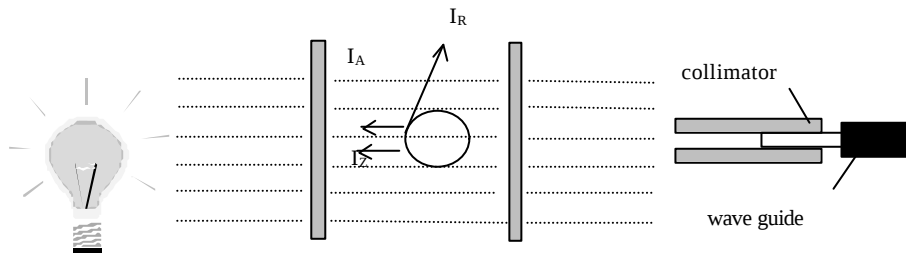


Fig. 3. Distribution of components of light intensity

Decrease of intensity of the light beam after the bubble meeting is determined from the following equation:

$$E = \log \frac{I_0}{I} = \log \frac{I + I_R + I_Z + I_A}{I}, \quad (1)$$

where I_0 is the beam intensity emitted by the source, I is the beam intensity received by the detector, I_R is the intensity of the beam dissipated by a bubble, I_Z is the intensity of the beam reflected from a bubble, I_A is the intensity of the beam absorbed by a bubble.

The presented measuring method allows to determine a bubble shape on the basis of detection of the

luminous flux in the visual field of the detector. Decrease of the light intensity of the ray passing through the liquid below the limit value informs us about that fact. The data obtained from measurements are in a binary form. Reconstruction of a bubble shape is possible as a result of application of the algorithm for image reconstruction.

2.2 Light source and detector

A light source is a fibre light bulb located in the centre of the concave mirror with a set of correcting lens (Fig.4a). The bulb should be cylindrical, its length should be more than a detector length. Such a shape enables to obtain uniform light beam intensity along the lightened section. Location of the bulb 1 in the mirror focus 2 provides obtaining parallel light rays in vertical direction. For better directing the beam in horizontal direction, a series of minilens 3 was applied.

A detector structure is shown in Fig. 4b. It contains a row of optical wave-guides 4 located in collimation sleeves 3. Application of an additional sensor allows to measure the bubble movement rate and, as a consequence, it is possible to determine its vertical diameter. For a model solution $s = 4$ mm. The system resolution is dependent on a distance R_x between the wave guides and the detector visual field which can be controlled by the collimation slot length of the wave-guide sensor. In the considered detector, it is 0.5mm. The collimation slot length is controlled by a displacement of a movable plate 1 with the fixed wave-guides in relation to a stationary plate 2 with the collimation sleeves.

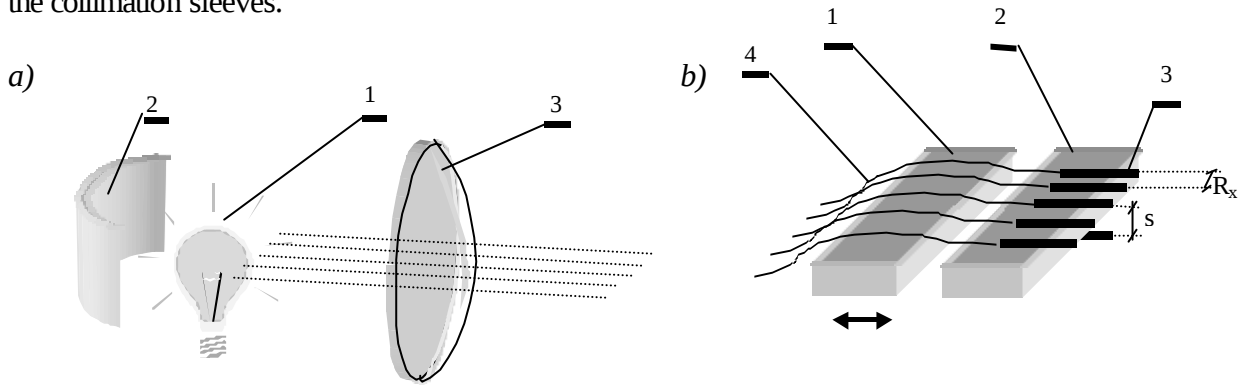


Fig. 4. a) Light source; b) Wave guide detector

2.3. Calculation of the flow volumes

Volume of the flowing gas bubbles is determined in a numerical way, with use of a suitable algorithm for reconstruction of bubble shape. On the reconstruction, a bubble shape is approximated by a series of cylinders (Fig.5) [2]. Bubble shapes are determined by volume determination by cylinders d_z in height.

Calculations of bubble volume include summation of volumes of cylinders included into one bubble. The equation for volume takes the following form:

$$V_w = \sum_{i=1}^{n-1} V_i = \frac{d_z p}{4} \sum_{i=1}^{n-1} d_{(i)}^2, \quad (2)$$

where V_i is the constituent volume of one slice, $d_{(i)}$ is the diameters of the cylinder of the i -th slice, d_z is the slice height, n is the number of slices forming a bubble.

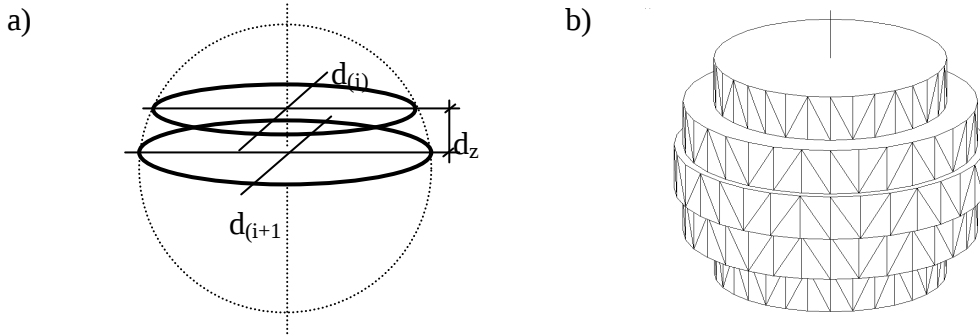


Fig. 5. Approximation of a bubble shape a) an idea; b) approximation by cylinders

Determination of the displacement d_z between particular ellipses includes calculation of a way travelled by a bubble between successive measurements. The way is dependent on the bubble motion rate and the sampling time, according to the equation:

$$d_z = w_n t_p, \quad (3)$$

where t_p is the sampling time, w_n is the bubble rate.

The bubble movement rate is determined from analysis of courses of the measuring signals coming from suitable optical probes located in the upper and bottom layers of the detector. The rates are determined on the basis of calculations of the mean time of the bubble passage.

$$w_s = \frac{s}{n_z t_p}, \quad (4)$$

where n_z is the mean number of clock cycles.

A number of the clock strokes n_z was determined by the correlation method. Determining a number n for which the correlation function reaches the maximum value, we have:

$$K_{\max} = \sum_{i=0}^{N_p - n_z} d_i^1 d_{i+n_z}^2, \quad (5)$$

where d^1 is the measuring data from the bottom sensor, d^2 is the measuring data from the upper sensor, N_p is the number of specimens of the tested signals.

3. Analysis of the gas gubble forming and their movement in a liquid

In the presented flow meter, the measuring accuracy is strongly influenced by a suitable selection of the nozzle diameter, from which the bubbles are getting away. In this case, a measuring range and a measuring error should be taken into account. In order to select a proper nozzle diameter, the authors analysed bubble formation and used a simplified dynamic model. In this model it is assumed that a bubble is like a ball and that there are no interactions between the considered bubble and other bubbles and the walls and the surrounding liquid is at rest. It is also assumed that the volume flowing through the pipe causes increase of the bubble volume. Any forces connected with

the gas compressibility are neglected in the considered model (Fig.6a).

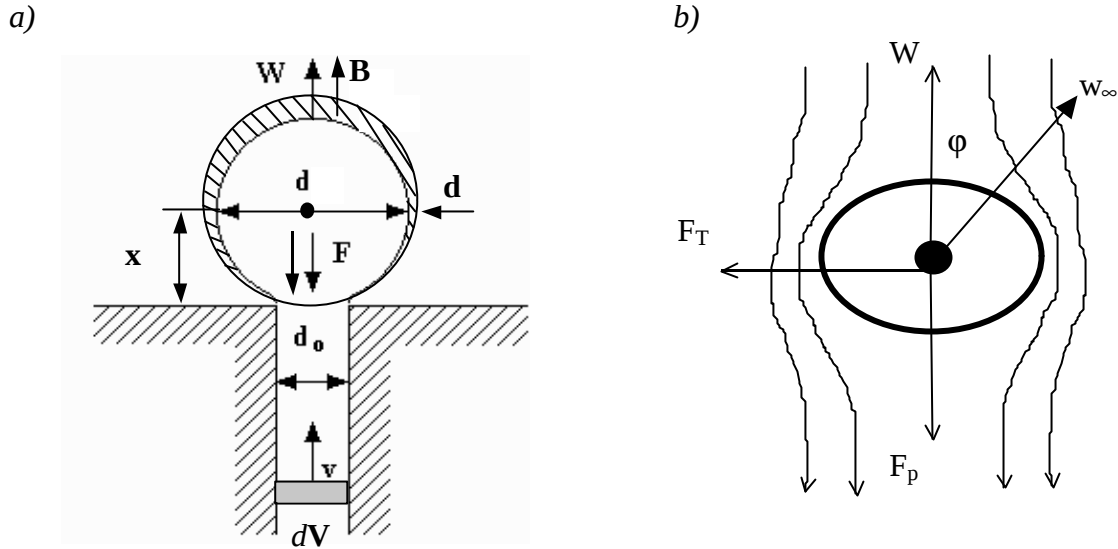


Fig. 6. Analysis of the gas bubble a) bubble formation in an unrestricted flow; b) distribution of forces acting on a bubble

Thus, the equation for the bubble diameter takes the following form:

$$d = \sqrt[3]{\frac{6 s d_0}{g (r_c - r_g)} + \frac{r_g}{(r_c - r_g)} \frac{d_0^2}{2g} v}, \quad (6)$$

where r_c is the liquid density, r_g is the gas density, d_0 is the hole diameter, g acceleration of gravity, v is the velocity of the gas flow from the nozzle, s is the coefficient of the liquid surface tension.

This model is valid for dynamic formation of bubbles, however, the flow out velocity must be rather small because it cannot cause bubble deformation.

A shape of the gas bubble moving in a liquid changes all the time because the moving bubble is subjected to the forces causing its deformations. It is a result of continuous changes of pressure distribution inside the bubble. Changes of a bubble shape directly influences velocity of its movement in the liquid.

Movement of a spherical bubble in an immovable liquid after covering a distance becomes approximately uniform. It is caused by equilibrium of forces acting on the bubble (Fig.6b). A gas bubble moving in the liquid is subjected to two main forces. One of them is the hydrostatic lift force W , it is directed upward and its value is according the Archimedes principle. The other force is directed downward and it is the resisting force, it acts oppositely to the bubble movement direction. This force is dependent only on velocity and it counteracts to the hydrostatic lift force. Deformations of the bubble shape are mainly caused by the resisting forces of the bubble movement. On the other hand, this force depends only on the bubble movement rate and the resistance coefficient.

Velocity of the moving bubbles can be determined from:

$$w_{\infty} = \sqrt{\frac{2g(r_c - r_g)V}{C_D r_c A}}, \quad (7)$$

where C_D is the resistance coefficient (Fig.7), A is the cross-section area of the bubble, V is the bubble volume.

Basing on analysis of the bubble movement we can select a suitable liquid for the flow meter. The Tadaka criterial number can be assumed as a criterion for selection. Its value should not exceed 5.5 [3, 4]. The Tadaka number can be defined as:

$$Ta = Re M^{0.23}, \quad (8)$$

where Re is the Reynolds number, M is the Morton number.

$$Re = \frac{w_{\infty} d r_c}{m_c} \quad (9)$$

$$M = \frac{g m_c^4 (r_c - r_g)}{r_c^2 s^3}, \quad (10)$$

where d is the bubble diameter, m_c is the orton number.

Such analysis is important because it is necessary to minimize measuring errors, shapes of bubbles should be regular. They should take the form of a sphere or a flattened elipsoid. Fig.7 presents changes of bubble shapes versus the Reynolds number.

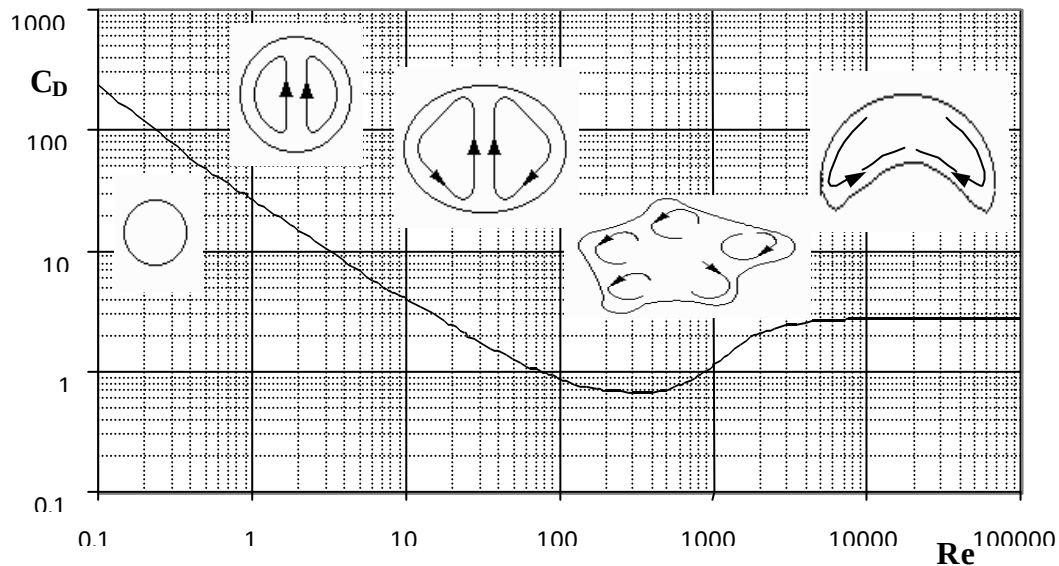


Fig. 7. The bubble shape on the Reynolds number

3. Tests and results of measurements the gas flow

During the tests, a constant gas flux was delivered from a diffusion pump. Its value was precisely determined. Next, the flow was measured with the flow meter. Fig. 8 shows a comparison of the test results. Six measurements were done for each flow value so it is possible to estimate the measurement uncertainty. The measuring points were approximated by a straight line. The broken line shows a deviation $\pm 10\%$ [6].

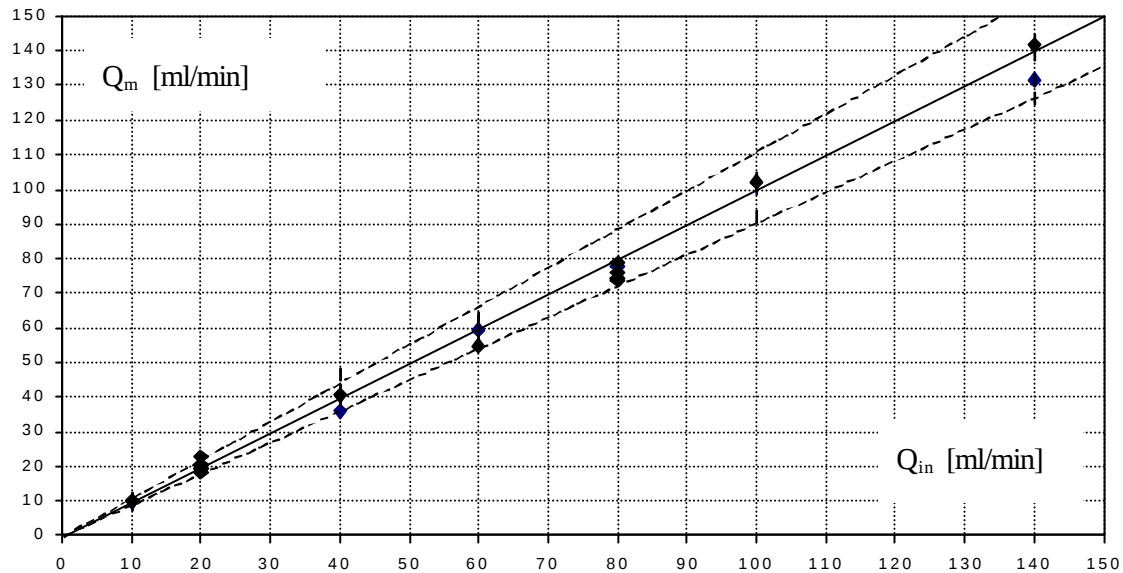


Fig. 8. Dependencies between uncertainty and flow

Properties of the light source can be improved by location of a light bulb in the focus of the concave mirror, application of the system of lenses and increase of the distance L between the light source and the measuring point. Flow measurements were done for the gas flux changing and unchanging at time.

The results are shown in Fig. 10. A gas of the constant flow intensity 40 ml/min was delivered to the flow meter. Since the flow is stationary, the bubbles generated in the flow meter should have similar dimensions and move with similar velocities. Increment of the measured volume of the flowing gas should be linear (see dark grey line).

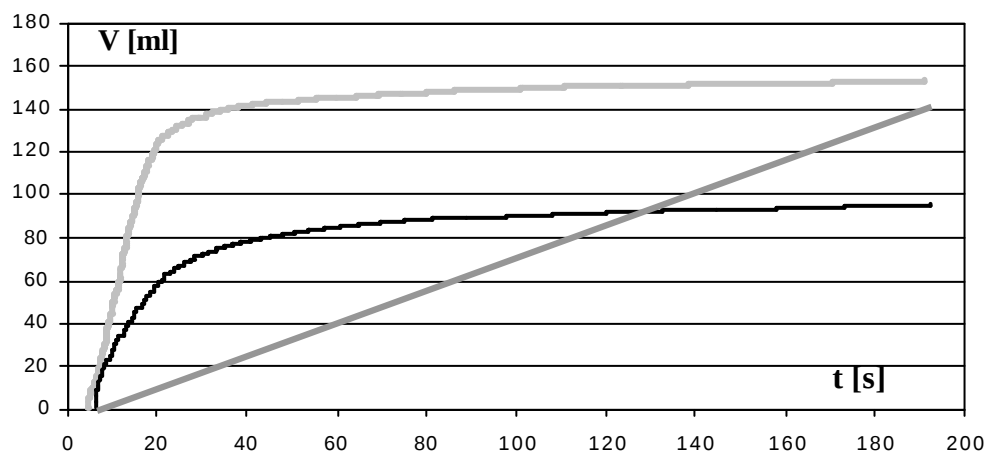


Fig. 10. Measurements of the variable flow at time a) volume increase at time; b) measuring error depending on a number of specimens of the tested signals

5. Conclusions

The presented method enables to measure very small flows under a low drop of the gas pressure. The measuring range is about some m^3/h . It is dependent on a flow meter structure. For a model flow meter the measuring uncertainty from the confidence interval 95% is included into 10% measured value. We can obtain decrease of the measuring uncertainty using a detector of less resolution and a light source of better convergence – for instance a laser with a set of semitransmitting mirrors [5]. The proposed solution was applied for measurements of gas emitted from moulding sands while drying where it satisfies the assumed requirements.

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