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METHOD FOR CALCULATING CONCENTRATION OF GAS IN A NON–TIGHT CONTAINER DURING GAS INTRODUCTION

There are two known methods of determining gas concentration in a container: the first one is based on IR and mass-spectrographic measurements with sample collection in several points; the second one is based on measuring the gas volume in an air-filled non-tight container with a flowmeter and concentration calculation. It is believed that the second option provides lower accuracy than the first one which is conditioned by gas leaking into the atmosphere from a non-tight container. We are showing the way of increasing the accuracy of determining gas concentration by the second method by way of calculating the leaked gas volume. It is maintained that the accuracy of the suggested method involving gas concentration determination with a flowmeter followed by calculation of its readings is not lower than the methods involving direct measurements, and that the cost of its implementation is one order less which provides evident competitive advantage.

Keywords: non-tight container; gas concentration calculation; flowmeter; mathematical model; gas supply process.

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Introduction

When tests involving gas explosion in containers are conducted, the issue of determining its concentration arises. In practice, this issue is solved in two methods. One of them is a direct instrument method [1–3], involving use of infra-red and mass-spectrographic instruments for measuring gas concentration. The other one is the widely-spread instrumentation-and-calculation method [4–6], which involves measurement of the volume of gas supplied to the chamber followed by calculation of its concentration based on the relation between its volume to the chamber capacity. It should be noted that in case of the direct measurement, the error is a combination of two factors — the error of the measuring instrument and the error related to the inhomogeneity of a large volume of gas mixture. In case of instrumentation-and-calculation method, the error shall also be a combination of two factors — the error of the flowmeter and the error of the calculation method. By comparing both methods, is may be noted that the accuracy of the first method is higher if the concentration changes in several points of the container. At the same time, the first method is more costly. If error of the instrumentation-and-calculation method involving the use of a flowmeter can be reduced, this method will become the most optimal.

The objective of this work is to reduce the error of the method for determining gas concentration in a non-tight container involving the use of a flowmeter to measure the output volume of gas. It is expected to reach the objective by improving the flowmeter readings calculation method. For this purpose, a mathematical model of gas supply to the container, its accumulation and outflow to the atmosphere was described.

Theory and calculations. Mathematical model

This mathematical model represents a conservation equation applied to gas contained in a container [7, 8]. To solve the equation, the assumption was accepted that the supplied volume of the gas equals the outflowing volume. In practical cases, the time during which this equation is not observed is negligible in comparison with the time during which the container is filled with gas [9]. The substantiation of the calculation method is presented in the form of a problem solution.

The container filled with air with a whole through which it contacts the atmosphere, is filled with gas at a known flow rate. What will gas concentration in the tank be after a fixed period of time from starting gas supply?

Pre-assumptions:

- gases are considered ideal in gas-dynamic sense;
- the gas mixture flowing out of the hole are has gas dynamic properties equal to those of the air and behaves like an incompressible fluid;

- the characteristic size of the gas input hole and the size of the atmospheric output are negligible in relation to the container size;
- the *gas – air* mixture has equal concentration throughout the container volume.

Conventional symbols:

V — the tank capacity, m^3;
v_1 — gas flow rate at the tank input, m^3/sec;
v_2 — the flow rate of gas-air mixture flowing from the tank to the atmosphere, m^3/sec;
p_0 — atmospheric pressure, Pa;
p — pressure inside the container, Pa;
ρ — air density, kg/m^3;
F — the cross-section of contact between the container and atmosphere, m^2;
V_{gas0} — the volume of gas supplied to the container, m^3;
V_{gas} — the volume of gas remaining in the container, m^3;
c — the precise calculated concentration of gas in the container;
c_0 — the concentration of gas in the container obtained by way of simplified calculation;
c_1 — the concentration of gas if no leak is assumed; $c_1 = (v_1/V)\,t = V_{gas}/V$;
t — the current time, sec;
δ — the volume of gas leaking from the container; $\delta = c_1 - c_0$.

1. The volume of gas in the container equals $V_{gas} = cV$, whereas its outflow rate to the atmosphere equals cv_2. Then, conservation equation applied to gas in the container at initial conditions $t = 0$, $c = 0$ shall be as follows:

$$\mathrm{d}(cV)/\mathrm{d}t = v_1 - v_2 c. \qquad (1)$$

It is considered here that the concentration of gas in the output stream equals 1.

As gas is supplied to the container, its pressure increases which leads to gas outflow to the atmosphere through leakages or special holes [10]. This happens until pressure in the container stabilizes and input and output flowrates even out, i. e.

$$v_1 = v_2. \qquad (2)$$

2. However, the transition period is short compared to the time period during which the container is filled with gas until the required concentration is reached. This task (comparison) is analytically completely solvable, however, it is quite bulky and therefore is not shown. Let's use common reasoning with a specific example.

Example 1

Let $V = 10$ m^3, $v_1 = 0.001$ m^3/sec, $F = 0.0001$ m^2, $\rho = 1.23$ kg/m^3.

Overpressure in the container in stable conditions shall be

$$p - p_0 = 0.5\,(v_1/F)^2\,\rho = 61.5 \text{ Pa}. \qquad (3)$$

The gas to be supplied to the container shall have volume ΔV:

$$\Delta V = (p - p_0)\,V/p_0 = 0.00615 \text{ m}^3. \qquad (4)$$

The time to supply the required volume of gas shall be $\Delta V/v_1 = 6.15$ sec. On the other hand, for gaining, for example, 5 % concentration, about 500 sec will be necessary. This indicates that the stabilization period is negligible in comparison to the container filling time.

Remark. Increase of the outflow hole reduces both, the pressure in the container, and the transition period.

3. Equation (1) is modified considering equation (2):

$$V(\mathrm{d}c/\mathrm{d}t) = v_1\,(1 - c). \qquad (5)$$

Dividing the variables:

$$\mathrm{d}c/(1 - c) = (v_1/V)\,\mathrm{d}t. \qquad (6)$$

Integrating both parts of the equation:

$$\ln(1 - c) = -(v_1/V)\,\mathrm{d}t + A, \qquad (7)$$

where A is an arbitrary constant.

The value of A shall be found using the initial conditions: $A = 0$.

The equation shall be exponentiated to obtain the required solution:

$$c = 1 - \exp\left(-\frac{v_1}{V}\,\mathrm{d}t\right), \qquad (8)$$

or in numerical variables

$$c = 1 - \exp(-c_1). \qquad (9)$$

Both equations, (8) and (9), allow to determine the exact concentration of gas in the container at any stage of gas injection (if the mixture in the container is well-mixed) [11]. However, it is not very convenient to use this equation, therefore, it shall be simplified.

The right part of equation (9) shall be expanded into a Maclaurin's series, confining to three members of the series:

$$1 - \exp(-c_1) = 0 + c_1 - c_1^2/2. \qquad (10)$$

From this follows the simplified method of calculating concentration c_0 based on c_1:

$$c_0 = c_1 - c_1^2/2, \qquad (11)$$

or (which is the same)

$$c_0 = c_1\,(1 - c_1/2). \qquad (12)$$

In practice, it is usually easier to prescribe a value to c_0, so that the amount of gas to be supplied with the account of leakage losses is known [12, 13]. For this purpose, equation (12) shall be presented as a quadratic equation:

$$c_1^2 - 2c_1 + 2c_0 = 0. \qquad (13)$$

By solving it in respect of c_1, the final equation shall be as follows:

$$c_1 = 1 - \sqrt{1 - 2c_0}, \quad (14)$$

or, the same one, using dimension values

$$V_{gas} = V(1 - \sqrt{1 - 2c_0}). \quad (15)$$

Based on equation (15), it is possible, by setting the required concentration of gas c_0 at the known capacity V of the container, to calculate the required volume of gas V_{gas}.

Example 2

Let $V = 10$ m^3 and the preset concentration $c_0 = 0.05$. Then, in order for leave 500 l of gas in the container, volume $V_{gas} = 10(1 - \sqrt{1 - 2 \cdot 0.05}) = 0.5132$ m^3 shall be supplied to the container, which equals 513.2.

Fig. 1,*a* shows three diagrams where gas concentration without regard to leaking is shown along the *x*-axis, and this may be considered the volume of gas supplied to the container. It follows from Fig. 1,*a* that, as the container is filled with gas, the pace of its concentration build-up decreases. It should also be noted that the functions calculated based on the accurate and the simplified formulas, start to deviate considerably at $c_1 > 0.4$. However, in the most practically interesting range of values of c_1 [0; 0.08] shown in Fig. 1,*b*, values of both calculation charts are practically converged; whereas at $c_1 = 0.08$, the difference near the right limit is less than 0.1 % or even less for other points of the range.

If gas leak is not taken into consideration and gas concentration in the container is considered to be c_1, then the difference between c_1 and c near the right limit of the operation range shall be around 2.6 %. This error may be treated differently depending on tasks at hand, including the cases where such error is unacceptable.

A simple analytic solution was obtained which does not depend on the volume of gas injected into the container, or the volume of atmospheric leak.

It should be noted that calculation results based on all the formulas are not influenced by the cross-section of the gas leak [14, 15]. This result is not fully obvious, but it is completely understandable from physical standpoint. The fact is that pressure inside the container is always higher than atmospheric pressure, because gas is injected into the container to prevent air ingress [16, 17]. This statement holds until outside pressure near the hole

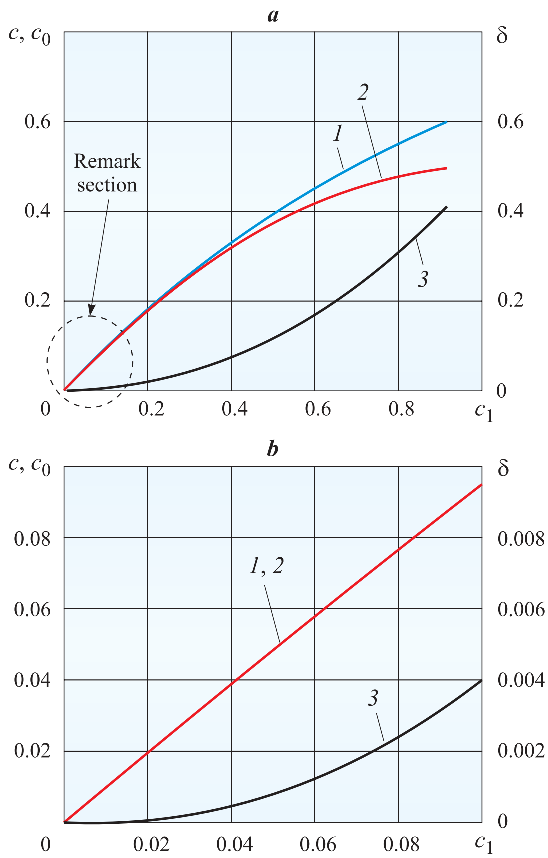

Fig. 1. Calculation charts for filling the container with gas: *1* — $c_0 = c_1(1 - c_1/2)$; *2* — $c = 1 - \exp(-c_1)$; *3* — $\delta = c_1 - c_0$

becomes higher than pressure inside the container due to any reasons, like wind pressure. However, wind pressure cannot last long, because pressure inside the container shall surely rise due further injection of gas which would compensate the wind pressure.

Conclusions

The considered method for determining concentration using flowmeters is more preferable than the method involving measurements in separate points of space, because it allows to determine the integral parameter value throughout the volume. Another advantage of using flowmeters is their lower cost in comparison to other measurement instruments [3, 18]. These facts combined with the use of formulas (14) or (15) for calculations, make the use of flowmeters for determining gas concentration in non-tight containers one of the most competitive.

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