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GAS DISTRIBUTION CONTROL SYSTEM USING MAGNETIC FLUID SENSORS

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Abstract. The paper presents a gas distribution control system, built using the inductive transducers with magnetic fluids (MF) for inclination and aerodynamic measurements. Using the functional principle of the differential pressure transducer for gases, we built flow rate transducers and flow meters for gases. We demonstrated the possibility of using these transducers in a N+1 flow meters network for gases, controlled by computer. Every N flow meters (customer flow meters) of a close range are supervised by another flow meter (supervisor flow meter) of higher range. The software of this structure can warn about any gases leakage in the network. In such a flow meters network, to perform an efficient supervision activity, the usually conditions (technical parameters) imposed to the transducers from the outside of a network (concerning the range, precision, sensitivity, etc.) are not enough anymore. Some supplementary conditions are required for the flow rate transducers in the network, especially for the supervisor flow rate transducer. The paper investigates the possibility to use (in such a flow meters network) flow rate transducers with linear reply time, and, the mathematical relations necessary to realise the supervisor software in this situation.

Key words: ferrofluids, magnetizable fluids, sensors, transducers, aerodynamics, gas flow rate, gas flow meter, reply time, answer time.

1. INTRODUCTION

Magnetic fluids (MF, [1]–[6]) or ferrofluids are usually defined as ultra-stable magnetic suspensions in different carrier liquids. These artificial liquid materials, having magnetic properties, present an excellent stability in the gravitational field and a very good stability in the magnetic field. Many applications of MF have been developed in the lasts years, in biology, medicine ([7], [8]), techniques ([9]–[14]), etc.

One of the technical applications of the MF is that of a magnetic liquid core for different electrical coils, usually belonging to some inductive transducers ([15]-[18]). From this type of transducers, we studied those for aerodynamic measurements and inclination ([19]–[26]). Using the functional principle of the transducer (sensor) for small differences pressure in gases ([27]–[29]), corrected for the influence of the inclinations and accelerations ([28], [30]), we built flow rate transducers and flow meters for gases ([16], [28], [30]).

The flow rate transducer (for gases) has as essential electrical components one pair of identical electrical coils, of circular cross section, uniformly wound. Every coil is placed around a carcass. The carcasses of the coils have the role of a vertical cylindrical reservoir for the MF. These two identical carcasses communicate at the bottom creating a vertical U-shaped tube, at equilibrium half filled with MF. At the top ends of the U-shaped tube, we placed a horizontal tube (called “laminar flow measuring element”). The gas flow rate (under measurement, denoted further by Q) passes through this horizontal tube creating a very small gas pressure difference between the two top ends of the U tube. This pressure difference produces a level gap between the MF from the two arms of the U tube, and leads to a difference between the inductances of the two coils. The inductance difference (evaluated using an electronic measuring system) becomes a measure for the gas flow rate, Q, from the horizontal tube.

We obtain the flow meter, integrating (electronically) in time the output electrical signal of the flow rate transducers. So, we have at the same time, the instantaneous gas flow rate value, Q, and the content of the gas flow meter (for a desired time period).

It is possible to use N+1 such flow meters with MF, in a flow meters network controlled by computer. Every N flow meters of closed range (further on called “customer flow meters”) are supervised by another flow meter (further on called “supervisor flow meter”) of higher range ([31], [32]). Theoretically, this structure can warn (by its software) about a gases leakage (or other problems) between the supervisor flow meter and the customer flow meters in the network.

In such a flow meters network, to perform an efficient supervision activity, the usually conditions (technical parameters) imposed to the transducers from the outside of a network (concerning the range, precision, sensitivity, etc.) are not enough anymore. Some supplementary conditions are required for the flow rate transducers in the network, especially for the supervisor flow rate transducer ([32]).

Through the supervisor, the average number of fluctuations (of the measured value Q) is the average number of fluctuations for customer transducers multiplied by the number N of the customer transducers. Because the supervisor flow rate transducer works very much in a transitory regime, one of the most important parameters for the supervisor flow rate transducer is the form of the answer (reply) time (not only the value of the reply time).

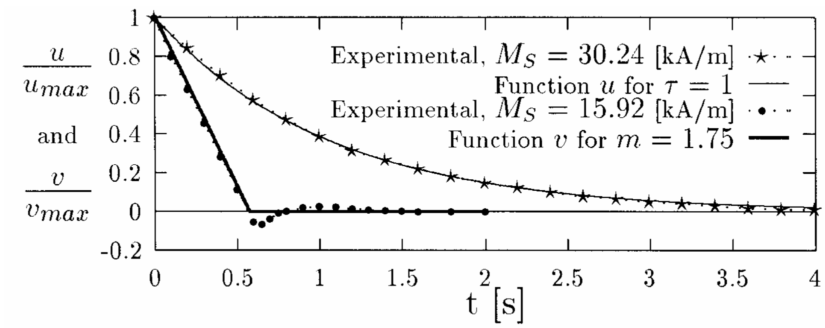


Fig. 1 – Experimental measurements concerning the reply time of the same flow rate transducer (and its theoretical approximations) for two samples of MF, having different saturation magnetization M_S (and different viscosities).

The reply time of this type of MF transducers, in different conditions, was experimentally studied in [27]. In [32], we presented the typical reply time of these transducers for a good (correct) damping of the MF column oscillatory motion. We showed that for a long reply time, the experimental results (Fig. 1) are excellently represented by the function (1). (In all the next equations the subscript E is for the End of the phenomenon, and, the subscript B is for the Beginning of the phenomenon.)

$$u(u_B, u_E, t) = \begin{cases} u_E + (u_B - u_E) \cdot e^{-\frac{t}{\tau}} & for \quad t \geq 0 \\ 0 & for \quad t < 0 \end{cases} \tag{1}$$

where u is the instantaneous value of the electrical output signal of the transducer, u_B and u_E are the electrical output signals at the beginning and at the end of the transitory regime, and, $\tau > 0$. (Usually, τ is between 1 and 2.)

We also showed that for a shorter reply time, the experimental results (Fig. 1) are well described by the functions (2) and (3).

$$v(u_B, u_E, t) = \begin{cases} sign(u_E - u_B) \cdot m \cdot t & for \quad 0 \leq t \leq \frac{|u_E - u_B|}{m} \\ u_E & for \quad t > \frac{|u_E - u_B|}{m} \\ 0 & for \quad t < 0 \end{cases} \tag{2}$$

where v is the instantaneous value of the electrical output signal of the transducer, $m > 0$ (usually, m is between 1 and 2), and,

$$sign(u_E - u_B) = \begin{cases} 1 & for \quad u_E - u_B \geq 0 \\ -1 & for \quad u_E - u_B < 0 \end{cases} \tag{3}$$

Supposing an arbitrary variation of the Q (presented in Fig. 2) the total gas flow passed through the laminar flow measuring element is:

$$\int_0^{\infty} Q(t) \cdot dt = \sum_{i=0}^{n} (t_{i+1} - t_i) \cdot Q_i = \sum_{i=1}^{n-1} (t_{i+1} - t_i) \cdot Q_i \tag{4}$$

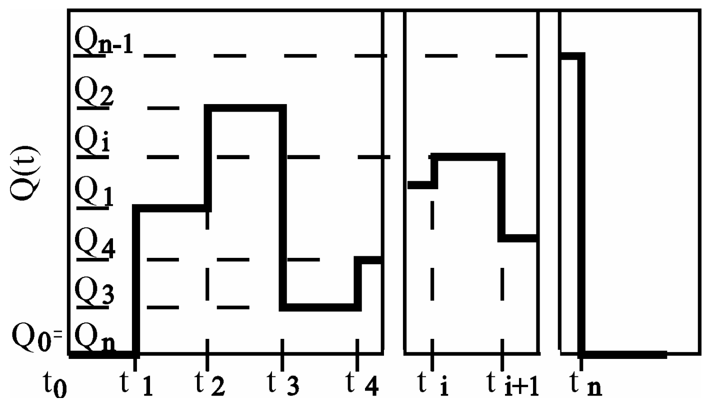


Fig. 2 – Supposed arbitrary values of the gas flow rate Q (through the laminar flow measuring element), *versus* time t.

It is known that, in a static regime (no Q variation, and the reply time of the transducer is finished), we can adjust the electronic circuits so that the electrical output signal of the flow rate transducer will be numerically equal to the Q value.

$$u_E = Q \tag{5}$$

So, the correct content (CC) of the flow meter counter is:

$$CC = \int_0^{\infty} Q(t) \cdot dt = \sum_{i=1}^{n-1} (t_{i+1} - t_i) \cdot u_{E,i} \tag{6}$$

Because of the reply time form, the content of the flow meter counter does not respect always the equality (6). In [32] we mathematically demonstrated that, if the reply time is given by the function u (equation (1)), the equality (6) is always true.

This paper presents the study of the flow meter content, when the reply time of the flow rate transducer is given by the function v (equation (2)).

2. ANALYTICAL CALCULUS OF THE FLOW METER CONTENT

Starting from the function (2), eliminating the function *sign* ((3)), and, taking into consideration that further on we work with v as function of t only, to simplify the written aspect, we redefine the function v, and we obtain:

$$v(t)=\begin{cases} u_B + k\cdot\dfrac{\Delta u}{|\Delta u|}\cdot t & \text{for} \quad 0\le t\le \dfrac{|\Delta u|}{k}; \\ u_E & \text{for} \quad \dfrac{|\Delta u|}{k}<t; \\ 0 & \text{for} \quad t<0, \end{cases} \tag{7}$$

where:

$$\begin{cases} k = constant; \\ k>0, \quad u_B\ge 0, \quad u_E \ge 0; \\ \Delta u = u_E - u_B . \end{cases} \tag{8}$$

For a segmented time domain as that presented in Fig. 2, we define the function:

$$v_i(t)=\begin{cases} u_{B,i} + k\cdot\dfrac{\Delta u_i}{|\Delta u_i|}\cdot (t-t_i) & \text{for} \quad t_i\le t\le t_i+\dfrac{|\Delta u_i|}{k}; \\ u_{E,i} & \text{for} \quad \dfrac{|\Delta u_i|}{k}+t_i<t; \\ 0 & \text{for} \quad t<t_i, \end{cases} \tag{9}$$

where:

$$\begin{cases} \Delta u_i = u_{E,i} - u_{B,i}; \\ 0\le t_0\le t_1\le \ldots \le t_i \le t_{i+1}\le \ldots \le t_n . \end{cases} \tag{10}$$

(Observation. For $t_i = 0$, $v_i(t)$ becomes $v(t)$. The time moment $t = t_i + \dfrac{|\Delta u_i|}{k}$ is the moment when $v_i(t) = u_{E,i}$.)

In this case, the total gas flow passed through the laminar flow measuring element is:

$$\int_0^\infty v(t)\cdot dt = \sum_{i=0}^{n} \int_{t_i}^{t_{i+1}} v_i(t)\cdot dt = \sum_{i=0}^{n} I_i \ . \tag{11}$$

Solving the integrals

$$I_i = \int_{t_i}^{t_{i+1}} v_i(t)\cdot dt \,, \tag{12}$$

we find two different situations.

1. One of these two situations is when v_i reaches the value $u_{E,i}$ before of the appearance of another transitory regime, that meaning

$$t_i + \frac{|\Delta u_i|}{k} \le t_{i+1} \, . \tag{13}$$

In this case,

$$v_i(t_{i+1}) = v_i\left(t_i + \frac{|\Delta u_i|}{k}\right) = u_{E,i} = u_{B,i+1} \,, \tag{14}$$

and, the integrals (12), will be denoted by $I_{i,1}$.

2. The other situation is when v_i no more reaches the value $u_{E,i}$ because another transitory regime starts, that meaning

$$t_i \le t_{i+1} < t_i + \frac{|\Delta u_i|}{k} \,, \tag{15}$$

$$v_i(t_{i+1}) = u_{B,i+1} \ne u_{E,i} = v_i\left(t_i + \frac{|\Delta u_i|}{k}\right), \tag{16}$$

and, the integrals (12) will be denoted by $I_{i,2}$. In the equation (16), instead of the sign "$\ne$", we use the sign "<" when $u_{E,i} > u_{B,i}$, and, the sign ">" when $u_{E,i} < u_{B,i}$.

2.1. CALCULUS OF THE INTEGRALS $I_{i,1}$

In this situation, every integral of (12) becomes a sum of two integrals.

$$I_{i,1} = \int_{t_i}^{t_{i+1}} v_i(t)\cdot dt = \int_{t_i}^{t_i+\frac{|\Delta u_i|}{k}} \left[u_{B,i} + k\cdot\frac{\Delta u_i}{|\Delta u_i|}\cdot(t-t_i)\right]\cdot dt + \int_{t_i+\frac{|\Delta u_i|}{k}}^{t_{i+1}} u_{E,i}\cdot dt =$$
$$= \int_{0}^{\frac{|\Delta u_i|}{k}} \left[u_{B,i} + k\cdot\frac{\Delta u_i}{|\Delta u_i|}\cdot t\right]\cdot dt + \int_{t_i+\frac{|\Delta u_i|}{k}}^{t_{i+1}} u_{E,i}\cdot dt. \tag{17}$$

After all the algebraic calculations,

$$I_{i,1} = u_{E,i}\cdot(t_{i+1}-t_i) - \frac{\Delta u_i\cdot|\Delta u_i|}{2k}. \tag{18}$$

If we consider that in (11), all the integrals have the form (18), we obtain

$$\sum_{i=0}^{n} I_{i,1} = \sum_{i=0}^{n} u_{E.i}\cdot(t_{i+1}-t_i) - \frac{1}{2k}\cdot\sum_{i=0}^{n}\Delta u_i\cdot|\Delta u_i|. \tag{19}$$

For $\Delta u_i > o,\ |\Delta u_i| = \Delta u_i$, and, for $\Delta u_i < o,\ |\Delta u_i| = -\Delta u_i$. So, for the last relation we find:

$$\sum_{i=0}^{n} I_{i,1} = \sum_{i=0}^{n} u_{E.i}\cdot(t_{i+1}-t_i) - \frac{1}{2k}\cdot\left(\sum_{i=0}^{n}\pm(\Delta u_i)^2\right). \tag{20}$$

(In the last equation we will use the sign plus when $u_{E,i} > u_{B,i}$, and the sign minus when $u_{E,i} < u_{B,i}$.)

In the formula (20), if we denote

$$\varepsilon = -\frac{1}{2k}\cdot\left(\sum_{i=0}^{n}\pm(\Delta u_i)^2\right), \tag{21}$$

then, the formula (20) becomes

$$\sum_{i=0}^{n} I_{i,1} = CC + \varepsilon. \tag{22}$$

2.2. CALCULUS OF THE INTEGRALS $I_{i,2}$

We solve below the integral $I_{i,2}$.

$$I_{i,2}=\int_{t_i}^{t_{i+1}} v_i(t)\cdot dt=\int_{t_i}^{t_{i+1}}\left[u_{B,i}+k\cdot\frac{\Delta u_i}{|\Delta u_i|}\cdot(t-t_i)\right]\cdot dt=$$

$$=\int_{0}^{t_{i+1}-t_i}\left[u_{B,i}+k\cdot\frac{\Delta u_i}{|\Delta u_i|}\cdot t\right]\cdot dt=u_{B,i}\cdot(t_{i+1}-t_i)+\frac{k}{2}\cdot\frac{\Delta u_i}{|\Delta u_i|}\cdot(t_{i+1}-t_i)^2= \quad (23)$$

$$=\frac{1}{2}\cdot(t_{i+1}-t_i)\cdot\left[2u_{B,i}+k\cdot\frac{\Delta u_i}{|\Delta u_i|}\cdot(t_{i+1}-t_i)\right]=\frac{1}{2}(t_{i+1}-t_i)[u_{B,i}+v_i(t_{i+1})].$$

If we take into consideration the first part (before the sign "$\neq$") of the relation (16), we obtain:

$$I_{i,2}=\frac{u_{B,i}}{2}\cdot(t_{i+1}-t_i)+\frac{u_{B,i+1}}{2}\cdot(t_{i+1}-t_i). \quad (24)$$

(Observation. To check the calculations we can observe that for $t_{i+1}=t_i+\frac{|\Delta u_i|}{k}$, we find the equality $I_{i,1}=I_{i,2}$.) (and also $=\frac{|\Delta u_i|}{k}\cdot\frac{u_{E,i}+u_{B,i}}{2}$.)

Considering again the equation (11), but all the integrals having the form (24) (and $I_{0,2}=0$), we obtain:

$$\begin{array}{lllll}
I_{1,2}= & \frac{u_{B,1}}{2}\cdot t_2 & -\frac{u_{B,1}}{2}\cdot t_1 & +\frac{u_{B,2}}{2}\cdot t_2 & -\frac{u_{B,2}}{2}\cdot t_1\\
I_{2,2}= & \frac{u_{B,2}}{2}\cdot t_3 & -\frac{u_{B,2}}{2}\cdot t_2 & +\frac{u_{B,3}}{2}\cdot t_3 & -\frac{u_{B,3}}{2}\cdot t_2\\
I_{3,2}= & \frac{u_{B,3}}{2}\cdot t_4 & -\frac{u_{B,3}}{2}\cdot t_3 & +\frac{u_{B,4}}{2}\cdot t_4 & -\frac{u_{B,4}}{2}\cdot t_3\\
I_{4,2}= & \frac{u_{B,4}}{2}\cdot t_5 & -\frac{u_{B,4}}{2}\cdot t_4 & +\frac{u_{B,5}}{2}\cdot t_5 & -\frac{u_{B,5}}{2}\cdot t_4\\
\vdots & \vdots & \vdots & \vdots & \vdots\\
I_{i,2}= & \frac{u_{B,i}}{2}\cdot t_{i+1} & -\frac{u_{B,i}}{2}\cdot t_i & +\frac{u_{B,i+1}}{2}\cdot t_{i+1} & -\frac{u_{B,i+1}}{2}\cdot t_i\\
I_{i+1,2}= & \frac{u_{B,i+1}}{2}\cdot t_{i+2} & -\frac{u_{B,i+1}}{2}\cdot t_{i+1} & +\frac{u_{B,i+2}}{2}\cdot t_{i+2} & -\frac{u_{B,i+2}}{2}\cdot t_{i+1}\\
\vdots & \vdots & \vdots & \vdots & \vdots\\
I_{n-1,2}= & \frac{u_{B,n-1}}{2}\cdot t_n & -\frac{u_{B,n-1}}{2}\cdot t_{n-1} & +\frac{u_{B,n}}{2}\cdot t_n & -\frac{u_{B,n}}{2}\cdot t_{n-1}\\
I_{n,2}= & \frac{u_{B,n}}{2}\cdot t_{n+1} & -\frac{u_{B,n}}{2}\cdot t_n & +\frac{u_{B,n+1}}{2}\cdot t_{n+1} & -\frac{u_{B,n+1}}{2}\cdot t_n
\end{array} \quad (25)$$

Adding these "n" equations of the system (25), we observe that the terms 2 (of the "i+1" equation) and the terms 3 (of the "i" equation) of the right side of the equalities, will disappear. Because $u_{B,1}=0$ and $u_{B,n+1}=0$ (we suppose that the measurements start and stop at zero flow rate), for the equation (11) we obtain:

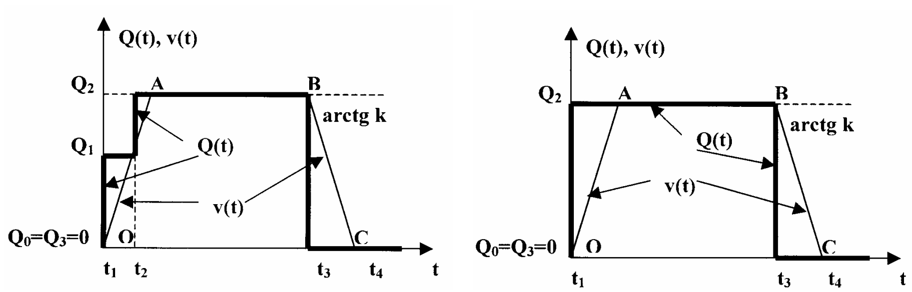
$$\sum_{i=0}^{n} I_{i,2} = \sum_{i=2}^{n} \frac{u_{B,i}}{2} \cdot \left(t_{i+1} - t_{i-1}\right) \tag{26}$$

3. PHYSICAL INTERPRETATION OF THE RESULTS

3.1. THE CASE OF THE FORMULA (20)

In the formula (20), if $\varepsilon = 0$ for any series of dynamical measurements, the formula (20) expresses the CC. (See also (22).)

As we suppose that the measurements start and stop at zero flow rate, the relation $\sum_{i=0}^{n} \Delta u_i = 0$ is true, but, that does not mean that $\left(\sum_{i=0}^{n} \pm\left(\Delta u_i\right)^2\right)$ from the equation (20) is zero.



a b

Fig. 3 – Real values of the gas flow rate Q(t) (thick line) and the output electrical signal of the flow rate transducer v(t) (thin line).

To understand better the physical phenomenon which takes place, it is enough to look at the particular case presented in Fig. 3 (a and b).

In Fig. 3 a, at the moment t_1 the gas flow rate rises from the value zero to the value Q_1, and at the moment $t_2 = t_1 + \frac{Q_1}{k}$ (when v(t) reaches the value Q_1) the gas flow rate rises from the value Q_1 to the value Q_2. At the moment t_3 the gas flow rate decreases from the value Q_2 to the value Q_3 =0. To apply the relation (20), we have initially

$$\begin{cases} I_{11} = Q_1(t_2 - t_1) - \dfrac{1}{2k}Q_1^2 , \\ I_{21} = Q_2(t_3 - t_2) - \dfrac{1}{2k}(Q_2 - Q_1)^2 , \\ I_{31} = Q_3(t_4 - t_3) + \dfrac{1}{2k}(-Q_2)^2 = \dfrac{1}{2k}Q_2^2 , \end{cases} \tag{27}$$

and the relation (20) becomes

$$\sum_{i=1}^{3} I_{i,1} = Q_1(t_2 - t_1) + Q_2(t_3 - t_2) + \frac{Q_1}{k}(Q_2 - Q_1). \tag{28}$$

So, in this case CC and ε have the values:

$$\begin{cases} CC = Q_1(t_2 - t_1) + Q_2(t_3 - t_2) \\ \varepsilon = \dfrac{Q_1}{k}(Q_2 - Q_1) > 0. \end{cases} \tag{29}$$

(The flow meter shows a higher consumed value than the real value.)

In Fig. 3 b, at the moment t_1 the gas flow rate rises from the value zero directly to the value Q_2, and, at the moment t_3 the gas flow rate decreases from the value Q_2 to the value $Q_3 = 0$. The relation (20) has in this case two terms only,

$$\begin{cases} I_{11} = Q_2(t_3 - t_1) - \dfrac{1}{2k}Q_2^2 , \\ I_{21} = Q_3(t_4 - t_3) + \dfrac{1}{2k}(-Q_2)^2 = \dfrac{1}{2k}Q_2^2 , \end{cases} \tag{30}$$

and,

$$\sum_{i=1}^{2} I_{i,1} = Q_2(t_3 - t_1) = CC . \tag{31}$$

(Observation. In both Fig. 3 a and b, the content of the flow meter is the same, given by the area of the isosceles trapeze OABC. In the case 3 b, the content of the flow meter is correct, but in the case 3 a, the content of the flow meter is affected by errors.)

Generally speaking, using formula (20) the flow meter content is correct only in the particular case when in the measurements time, for every flow rate increasing by a certain value, sooner or later a flow rate decreasing by the same value will appear (and *vice versa*).

3.2. THE CASE OF FORMULA (26)

Obviously, formula (26) does not offer the CC value. So, in this case we can't say that we measure the gas flow rate. The content of a counter working in this regime (and its flow rate indication) is determined by the start point of the measurements. For example, a flow rate transducer which starts from zero and measures a gas flow rate having a periodical rectangular form (the flow rate has a certain value in 50% of the period, and, in 50% of the period the flow rate is zero), will deliver at its output a periodical electrical signal having the form of isosceles triangles. These triangles have their bases on the Ox axis, and their height (and the flow meter value) proportional to the period of the rectangular flow rate.

If (when we start to apply to this flow rate periodical rectangular impulses) the output of the flow rate is not at zero, but at a certain value, the isosceles triangles will have their bases on a horizontal right line, parallel to the Ox axis, but having the ordinate at this certain value.

4. CONCLUSIONS

In the pyramidal gas distribution system controlled by computer, it is more difficult to use (the software is more complicated) the flow rate transducers (flow meters) having linear answer time than the transducers having exponential reply time.

In a distribution system having the supervisor flow rate transducer described by formula (20), analyzing the output signals of the customer flow rate transducers, we can obtain information concerning the error value (ε). So, we can eliminate the error from the formula (20), and, we obtain the CC value. From this point, the supervising activity will use a software similar to the software from the flow rate transducers having exponential reply time.

In a distribution system having the supervisor flow rate transducer described by formula (26), we can't speak about a supervision through a global measurement. With all these, using a more complicated software algorithm and numerical systems of higher performances, it is still possible to detect the gas leakages.

The calculus relations described above (especially (20) and (26)) allow to realize the supervision software for the pyramidal distribution systems, of any (consumable) physical material measurable using linear answer time transducers.

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