Measures to Improve Metrological and Technical Characteristics of the Film Gas Flowmeter

Oksana Parneta[*], Ivan Stasiuk, Ihor Dilay, Ihor Demkiv

Lviv Polytechnic National University, 12 Stepana Bandery St., Lviv, 79013, Ukraine

Abstract

The problems of low flow rate measurement (in particular, increasing the accuracy and expanding the measurement range) are relevant both in modern technologies and in experimental studies. The error of a film flowmeter depends on its design, the quality of calibration, as well as the properties of the gas under study and the film-forming liquid. The paper considers the issues of optimizing the composition of the film-forming liquid of a film flowmeter in order to improve the accuracy of measuring the gas microflow rates. The possibility of increasing the lifetime of films by introducing a stabilizer, i.e. a high-molecular-weight impurity (polymer) polyacrylamide (PAM), into the film forming liquid has been studied. The properties of films formed from various solutions have been studied, the optimal composition of a film-forming agent have been obtained using PAM and it has been proposed to use it in film flowmeters in order to improve the accuracy and reliability of measuring the gas microflow rates. The paper also focuses on the mechanism of gas transfusion through the film and assesses its impact on the accuracy of flow measurement, as well as provides recommendations for reducing (eliminating) the error due to the effect of transfusion. The influence of a filmformer layer inside the measuring tube and the conditions of its existence have been studied, and the properties of the inner surface of the measuring tube have been considered, in particular, the matte finish of the inner surface of the tube.

Keywords: film flowmeter; measuring tube; gas flow measurement; soap flowmeter; film-forming liquid.

1. Introduction

A film flowmeter is mainly used to measure the gas small and micro flow rates [1]. This is primarily due to the possibility of its seemingly simple design and calibration, which, with low requirements for measurement quality, provides advantages over other measuring instruments. In its simplest version, such flowmeter consists of a glass measuring tube (a measuring burette) connected through a tee with an elastic cylinder filled with a soap solution [2], and a manual stopwatch. This design not only results in a rather narrow measurement range (1 ... 100 l/h), inferior operational and metrological characteristics of the device, but also in many cases makes it a mere flow indicator, and in some cases renders measurement impossible [2]. At the same time, the potential capabilities of the film measurement method are quite high and allow creating the high-quality flowmeters in the range of $10^{-5}...10$ m^3/h.

A measuring tube with a layer of the film-forming liquid on its inner surface and a moving film are the defining elements of a film flowmeter, directly determining the accuracy, reliability and range of measurement.

The measurement accuracy is significantly influenced by changes in the shape and geometric dimensions of the film on the inner surface of the measuring tube, which depend mainly on the properties of the film-forming liquid and those of the surface of the measuring tube, which must ensure wettability close to the boundary value. The requirements for film-forming liquids include the ability to form strong and relatively thick films of significant dimensions (for example, for measuring tubes with a diameter of up to 10 cm) with a lifetime in the measuring tube of at least 15 minutes; good wetting properties; all components of the film former must have a saturated vapour pressure by one or two orders of magnitude less than that of water; invariance of properties over time; chemical inertness and nontoxicity; scarcely dissolve gases and have low gas diffusion coefficients; non-hygroscopic properties; optical properties corresponding to the selected light source and film position lock; create no foam; leave no marks on the inner surface of the measuring tube.

The film-forming liquid includes a surfactant and a solvent. Other substances are also added in small quantities to improve the properties of a film-forming agent (enhancer, defoamer, etc.). It should be noted that the properties of the film-forming liquid have a significant effect on the measurement range of the film flowmeter, as well as its operational and metrological characteristics.

2. Analysis of the recent publications and research works on the problem

It can be seen from literary and patent sources that aqueous solutions of surfactants are mainly used as film-forming liquids for film flowmeters [1]-[13]. The main disadvantages of such solutions are film instability, significant gas permeability through the film and significant solubility of most gases with the formation of by-products, which leads to an increase in the measurement error of the film flowmeter. The high-boiling liquids such as formamide, ethylene glycol and glycerin are also used as a solvent for surfactants [14, 15], which allows increasing the measurement accuracy by reducing the error component due to the evaporation of the solvent and its saturation with the gas under study (at $t = 22$ °C, the saturated vapour pressure of water is $P = 20$ mm Hg, and for ethylene glycol $P = 0.2$ mm Hg). In addition, these liquids are chemically inert and have a lower gas solubility, which also contributes to an increased measurement accuracy.

The household detergents are usually used as surfactants. The disadvantages of these detergents include, first of all, the ageing of the film-forming liquid [14], a significant thickness of the film former layer on the inner walls of the measuring tube, insufficient lifetime of moving films, and alkaline properties. Such properties of household detergents lead to a significant narrowing of the measurement range, as well as the additional measurement errors, which in some cases can amount to up to 4 % [14]. Therefore, to enhance the surface activity of the solvent, it is recommended to use the higher hydroxyethyl fatty alcohols (e.g., synthanol DS-10) or the non-ionic surfactant OP-7 (OP-10) [14], that do not have the above-mentioned disadvantages.

To increase the strength and the lifetime of films, it is promising to add high-molecular-weight compounds such as polyacrylamide and polyvinyl alcohol, etc. to the surfactant solution [16]. The use of enhancers allows extending the upper limit of flow measurements significantly.

It is proposed to use a film-forming liquid containing ethylene glycol and synthanol in a ratio of 4:1, by volume, in the paper [14]. Ethylene glycol as a solvent is a dihydric aliphatic alcohol, an oily, colorless and odorless liquid with a boiling point of 197.6 °C. Synthanol DS-10, which belongs to hydroxyethyl higher fatty alcohols, is used as a surfactant. The mixture should be heated to a temperature of 50 ... 60 °C and mixed well to dissolve synthanol DS-10 in ethylene glycol.

3. Formulation of the goal of the paper

The influence of surface phenomena on the characteristics of a film flowmeter has not yet been sufficiently covered and requires research for specific measurement conditions (the gas under study, materials used in the film flowmeter, etc.). The goal of this paper is to study the influence of the properties of the film-forming liquid and surface phenomena on the performance characteristics of a film flowmeter and the accuracy of gas flow measurement. The authors' task was to study and analyse the filmformer layer inside the measuring tube and the

conditions of its existence, gas diffusion through the film, and the properties of the inner surface of the measuring tube (surface wettability, matte surface).

4. Studying the factors affecting the characteristics of the flow meter

The films formed from the solution proposed in the paper [14] are quite stable at low gas flow rates (up to 10 l/h) and a small diameter of the measuring burette (up to 15 mm). However, with an increase in the gas flow rate, the operation of the flowmeter is not reliable enough due to the loss of film stability. The studies conducted by the authors showed that the maximum strength of the films is at a different concentration of synthanol in ethylene glycol. Such studies were carried out using glass rings with a diameter of $d = 50$ mm. The ring was immersed in a vessel with a film-forming solution, and a film was formed when the ring was lifted from the solution. The lifetime of the films was measured. The number of measurements for each concentration was $n = 18$. The results of experimental studies were processed according to the standard method. Fig.1 shows the dependence of the lifetime τ of films on the concentration r of synthanol in a solution with ethylene glycol as a solvent based on the results of experimental measurements.
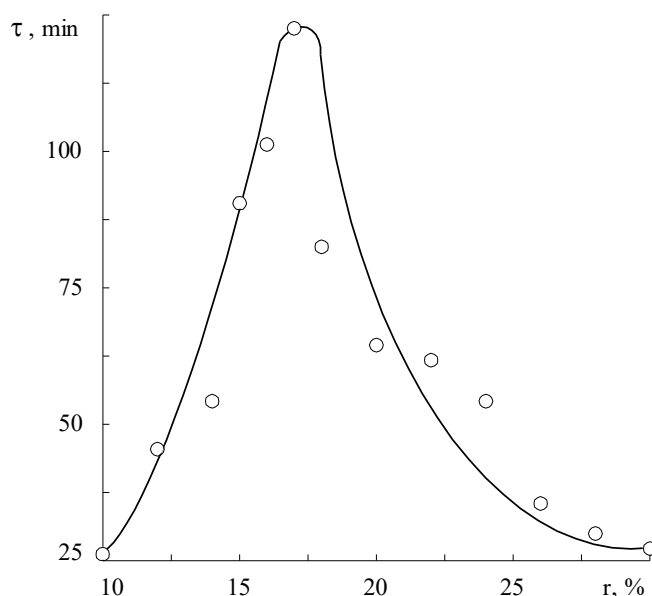

Fig.1. Dependence of film lifetime τ on synthanol concentration r in a film-forming solution.

It can be seen from Fig.1 that this dependence has an extremum in the duration of lifetime of the film from this solution. The maximum lifetime of the film is observed at a concentration of synthanol in ethylene glycol $r = 17$ %.

In order to increase the stability of the films, a polymer, powdered polyacrylamide (PAM), was added to this solution and its effect on the lifetime of the films in the film flowmeter was studied. Table 1 shows the measurement results.

Table 1. Dependence of film lifetime τ on PAM r_{PAM} concentration
in ethylene glycol + synthanol solution (17 %).

r_{PAM}, %	τ, min	r_{PAM}, %	τ, min
0.05	140.9	0.125	52
0.075	175.6	0.15	37.2
0.1	190.0	-	-

As can be seen from Table 1, the maximum film lifetime is observed at a PAM concentration in the solution of $r_{PAM} = 0.1$ %. With an increase in the polymer concentration, the film lifetime decreases sharply.

Based on the results of the studies performed, it is recommended to use a film-forming solution in the film flowmeter, the composition of which is as follows: ethylene glycol + synthanol (17 %) + PAM (0.1 %). Films formed from such solution are suitable for use in a film flowmeter at a flow rate of up to 120 l/h (measuring burette diameter $d = 50$ mm). It is important that the curvature of the films formed from this solution is small.

When measuring the flow rate of different gases (not air), such as H_2, CO_2, CH_4, with the open-air outlet of the flowmeter measuring tube, the gas dose under the film can be changed due to the transfusion of gases through the moving film [17], [18]. The reason for this process is the difference in the partial pressure of gases on both sides of the film: the partial pressure of the air components above the film is higher than under the film, and the partial pressure of the gas under study (pure or its components) above the film is lower. The effect of gas transfusion through the film on the measurement accuracy has hardly been studied, so it was necessary to estimate the magnitude of the measurement error caused by gas transfusion through the moving film and to develop recommendations for its reduction.

The process of gas flow through a double-sided liquid film in the direction of lower partial pressure has three stages: gas dissolution in the surface layer of the film on the side of higher partial pressure, diffusion through the liquid layer of the film and release (desorption) of gas on the opposite side of the film. The diffusion movement of gas in the liquid layer can be caused by different driving forces. Molecular diffusion occurs with different gas concentrations in the liquid on opposite sides of the film. Besides, gas dissolved in the liquid can move together with it. Such movement of gas is convective diffusion. However, the thickness of liquid films, as a rule, does not exceed 10 μm, therefore, the effect of convective diffusion on gas movement is insignificant and Fick's law of diffusion equation was used for the calculation.

According to Fick's first law, for a one-dimensional gas flow, its quantity (volume) dV transferred through the cross-sectional area A in $d\tau$ time is proportional to dC/dh gradient of gas concentration C over the film thickness h:

$$\frac{dV}{d\tau} = -DA\frac{dC}{dh}, \tag{1}$$

where D is the molecular diffusion coefficient.

For steady-state diffusion condition, the equation can be written as:

$$\frac{dC}{dh} = \frac{\Delta C}{h}, \tag{2}$$

where ΔC is the difference in concentrations of the diffusing gas in the near-surface layers of the film.

According to Henry's law, the concentration of gas (pure or its components) in the near-surface layer of liquid in equilibrium is equal to:

$$C = \beta p, \tag{3}$$

where β is the gas solubility coefficient; p is the partial pressure of gas near the surface of the film.

Thus, taking into account (2) and (3), the volume flow rate q of gas diffusing through a flat liquid film is described by the equation:

$$q = \frac{dV}{d\tau} = -DA\beta\frac{\Delta p}{h}, \tag{4}$$

where Δp is the difference in partial pressures of gas in the media separated by the film.

Gases dissolve poorly in typical liquids at low pressure [19]. With some exceptions (e.g., hydrogen), the solubility of any gas in typical solvents decreases with increasing temperature. The values of solubility β of some common gases in water at 20 °C and atmospheric pressure are given in Table 2 [20].

Table 2. Solubility β of gases in water at 20 °C and atmospheric pressure.

Gas	N_2	O_2	H_2	CO_2	CH_4	Ar	He
β, (m^3 of gas)/(m^3 of water)	0.016	0.031	0.0182	0.878	0.0331	0.0336	0.0088

The diffusion coefficient D is a constant of proportionality between the flow rate of gas diffusing through a flat liquid film and the driving force of diffusion (e.g., concentration gradient) [19].

The rate of gas diffusion flow can be determined experimentally by the rate of movement of a liquid film, which is formed in a cylindrical tube and separates media filled with different gases (e.g., carbon dioxide and nitrogen or air) at the same pressure [17]. During diffusion flow, due to different gas solubility and diffusion rates, a pressure difference occurs and the film begins to move along the tube, which leads to gas pressure equalization. If the solubility coefficient of one of the gases is much larger than $\beta_1 \gg \beta_2$, the rate of film movement is determined mainly by the diffusion rate of the most soluble gas.

Table 3 shows the values of diffusion coefficients of some common gases in water, determined by calculation using the Hayduk-Laudi and Wilke-Chang correlations, as well as some D_{AW} values obtained experimentally [19], [20].

Table 3. Diffusion coefficients D_{AW} of gases in water.

Gas	t, °C	D_{AW}, cm^2/s		
		Hayduk-Laudi Correlation	Wilke-Chang Method	Experimental values
N_2	18	$1.61 \cdot 10^{-5}$	$1.74 \cdot 10^{-5}$	
	20	$1.71 \cdot 10^{-5}$	$1.85 \cdot 10^{-5}$	
	25	$1.96 \cdot 10^{-5}$	$2.12 \cdot 10^{-5}$	$1.9 \cdot 10^{-5}$
	29,6	$2.21 \cdot 10^{-5}$	$2.38 \cdot 10^{-5}$	
O_2	18	$1.81 \cdot 10^{-5}$	$1.96 \cdot 10^{-5}$	
	20	$1.92 \cdot 10^{-5}$	$2.08 \cdot 10^{-5}$	
	25	$2.2 \cdot 10^{-5}$	$2.38 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$; $2.41 \cdot 10^{-5}$
	29,6	$2.48 \cdot 10^{-5}$	$2.68 \cdot 10^{-5}$	
H_2	18	$2.56 \cdot 10^{-5}$	$2.79 \cdot 10^{-5}$	
	20	$2.71 \cdot 10^{-5}$	$2.95 \cdot 10^{-5}$	
	25	$3.1 \cdot 10^{-5}$	$3.38 \cdot 10^{-5}$	$5.85 \cdot 10^{-5}$; $4.8 \cdot 10^{-5}$
CO_2	18	$1.53 \cdot 10^{-5}$	$1.66 \cdot 10^{-5}$	
	20	$1.63 \cdot 10^{-5}$	$1.75 \cdot 10^{-5}$	
	25	$1.86 \cdot 10^{-5}$	$2.01 \cdot 10^{-5}$	$1.96 \cdot 10^{-5}$
CH_4	18	$1.44 \cdot 10^{-5}$	$1.56 \cdot 10^{-5}$	
	20	$1.53 \cdot 10^{-5}$	$1.65 \cdot 10^{-5}$	$1.49 \cdot 10^{-5}$
	25	$1.75 \cdot 10^{-5}$	$1.89 \cdot 10^{-5}$	
Ar	18	$1.78 \cdot 10^{-5}$	$1.93 \cdot 10^{-5}$	
	20	$1.89 \cdot 10^{-5}$	$2.04 \cdot 10^{-5}$	
	25	$2.17 \cdot 10^{-5}$	$2.35 \cdot 10^{-5}$	
He	18	$2.11 \cdot 10^{-5}$	$2.29 \cdot 10^{-5}$	
	20	$2.23 \cdot 10^{-5}$	$2.43 \cdot 10^{-5}$	
	25	$2.56 \cdot 10^{-5}$	$2.78 \cdot 10^{-5}$	

As can be seen from Table 3, the values of coefficients of gas diffusion in water determined using different methods are close to each other, so they can be used to assess the effect of gas transfusion on the measurement accuracy of a film flowmeter.

We will demonstrate the assessment of this error on the example of measuring the flow rate of hydrogen H_2 using a film flowmeter. The partial pressure of the air components (nitrogen N_2 and oxygen O_2) above the film are higher than under the film, and the partial pressure of the light gas H_2 above the film is lower. Therefore, during the flow measurement,

hydrogen H_2 diffuses upwards through the moving film in the measuring tube, and nitrogen N_2 and oxygen N_2 diffuse downwards. The flow rate q_{H2} of hydrogen diffusing in the measuring tube of the flowmeter can be determined by formula (4). The flow rates q_{N2}, q_{O2} of nitrogen and oxygen diffusing from the air can also be determined by formula (4).

Data for the calculation:

- film area: $A = \pi d^2/4$ (d is the diameter of the measuring tube);
- film thickness: $h = 10^{-5}$ m;
- diffusion coefficients of H_2, N_2 and O_2 in water at 20 °C – D_{H2W}, D_{N2W}, D_{O2W} (Table 3);
- solubility of H_2, N_2 and O_2 in water at 20 °C – β_{H2}, β_{N2}, β_{O2} (Table 2);
- molecular weight: $M_{H2} = 2$ g/mol; $M_{N2} = 28$ g/mol; $M_{O2} = 32$ g/mol;
- density: $\rho_{H2} = 0.09$ kg/m^3; $\rho_{N2} = 1.25$ kg/m^3; $\rho_{O2} = 1.43$ kg/m^3;
- diffusion duration (flow measurement time): $\tau = 300$ s.

The volume V of gas diffusing through the film in the measuring tube of the film flowmeter during the flow measurement time τ:

$$V = V_{H2} - (V_{N2} + V_{O2}),\qquad(5)$$

where $V_{H2} = q_{H2}\tau$ is the volume of Hydrogen; $V_{N2} = q_{N2}\tau$ is the volume of Nitrogen; $V_{O2} = q_{O2}\tau$ is the volume of Oxygen.

The error of gas flow measurement by the film method due to gas diffusion through the film:

$$\delta_{dif} = \frac{V}{V_{m.t.}} 100\%,\qquad(6)$$

where $V_{m.t.}$ is the calibrated volume of the measuring tube of the film flowmeter.

The results of assessing the influence of H_2 gas diffusion for different measuring tubes during the flow measurement by the film method are given in Table 4.

Table 4. Assessing the influence of gas diffusion for different measuring tubes of the flowmeter.

		H$_2$		CH$_4$		N$_2$		O$_2$		He		Ar	
d, cm	$V_{m.t.}$, ml	V, ml	Δ_{dif}, %	V, ml	δ_{dif}, %	V, ml	Δ_{dif}, %	V, ml	δ_{dif}, %	V, ml	δ_{dif}, %	V, ml	δ_{dif}, %
0.5	2	0.009	0.48	0.01	0.51	-0.005	-0.227	0.016	0.79	-0.01	-0.47	0.018	0.92
0.7	5	0.016	0.32	0.02	0.35	-0.008	-0.15	0.03	0.54	-0.016	-0.32	0.03	0.63
0.8	10	0.02	0.24	0.03	0.26	-0.01	-0.116	0.04	0.41	-0.02	-0.24	0.05	0.47
1.1	25	0.05	0.19	0.05	0.21	-0.02	-0.09	0.08	0.33	-0.05	-0.19	0.09	0.38
1.4	50	0.07	0.14	0.08	0.15	-0.03	-0.066	0.12	0.23	-0.07	-0.14	0.13	0.27
1.8	100	0.12	0.12	0.13	0.13	-0.06	-0.057	0.20	0.20	-0.12	-0.12	0.23	0.23
2.5	200	0.23	0.115	0.25	0.12	-0.11	-0.055	0.39	0.19	-0.23	-0.113	0.45	0.22
2.7	250	0.27	0.11	0.29	0.116	-0.13	-0.05	0.45	0.18	-0.26	-0.106	0.52	0.21
3.6	500	0.48	0.09	0.52	0.104	-0.23	-0.046	0.81	0.16	-0.48	-0.095	0.94	0.19
4.4	1000	0.75	0.08	0.80	0.08	-0.36	-0.036	1.25	0.13	-0.73	-0.07	1.45	0.15
6.0	2000	1.38	0.07	1.49	0.07	-0.66	-0.03	2.32	0.12	-1.36	-0.068	2.69	0.13

Similarly, the flow measurement errors due to gas diffusion through a moving film were determined for pure gases such as methane CH_4, nitrogen N_2, oxygen O_2, helium He and argon Ar. The results of assessment of these errors are given in Table 4.

As can be seen from Table 4, the flow measurement errors due to gas transfusion for small-volume measuring tubes can reach 1 % (for example, for argon). Therefore, to ensure accurate measurements, the transfusion process must be taken into account and measures must be taken to reduce the specified error. To reduce gas transfusion through the film during the flow measurement, it is necessary to prevent the difference in partial pressure. The easiest way to do this is to bend the outlet end of the flowmeter measuring tube downwards. To reduce the difference in

partial pressures of gases, we also recommend passing the film through the flowmeter tube several times before measuring the flow (especially for gases that differ significantly in composition from air).

The measurement accuracy is significantly affected by errors from changes in the shape and geometric dimensions of the film on the inner surface of the measuring tube, determined mainly by the properties of the film-forming liquid and the properties of the surface of the measuring tube, which should ensure wettability close to the boundary value. For this purpose, we propose matting the inner surface of the measuring tube of the film flowmeter.

Glass matting can be performed chemically, which involves treating the glass surface with hydrofluoric acid mixed with its salts (e.g. ammonium fluoride, sodium fluoride or potassium fluoride) [21]. Hydrofluoric acid itself dissolves glass, but does not make it matte, so its salts should be necessarily mixed with it. Potassium fluoride salts give the most delicate matte surface and ammonium fluoride gives the roughest surface. Etching can also be done without hydrofluoric acid, using only its salts with an admixture of sulfuric or hydrochloric acid.

The studies of smooth and matte tubes with different film-forming liquids for the purpose of their comparison were carried out experimentally using the device, the schematic diagram of which is shown in Fig.2 [21]. Such studies consisted of measuring the electrical resistance R of the film-forming liquid layer formed on the inner surfaces of the measuring tubes due to their complete wetting. The metal ring electrodes were glued into the upper and lower ends of the tubes (smooth and matte). A solution of shampoo + water (1:10) (in volume) was used as a film-forming liquid. The length of measuring tubes was $l = 390$ mm, and the diameter of measuring tubes was $d = 20$ mm, gas flow rate was 10 l/h. The results of measuring the change in time τ (from the beginning of the experiment) of the electrical resistance R of the film-forming liquid layer inside the measuring tubes (smooth and matte) after the film passed through the calibrated section of the tube are given in Table 5 and Table 6.
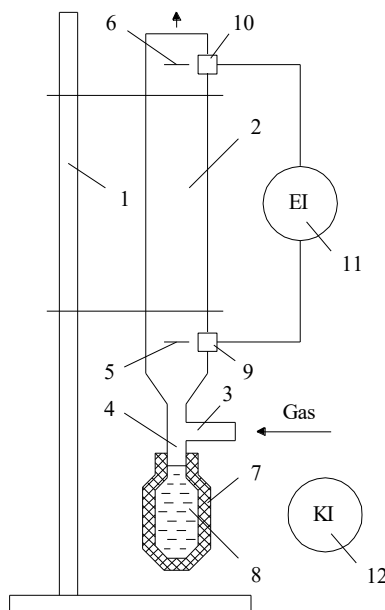

Fig.2. Schematic diagram of the device for studying measuring tubes of a film flowmeter with different film-forming solutions: 1 – stand; 2 – measuring tube; 3, 4 – pipes for supplying gas and film-forming solution to the measuring tube inlet, respectively; 5, 6 – marks limiting the calibrated section of the measuring tube; 7 – elastic reservoir; 8 – film-forming solution; 9, 10 – electrical contacts built in at the level of marks 5 and 6; 11 – electrical resistance meter; 12 – chronometer.

The increase in the electrical resistance R of the film-forming liquid layer on the inner surface of the measuring tube indicates a decrease in the thickness of this layer, i.e. its drying and flowing down. The matte finish of the inner surface of the measuring tube ensures several times larger durability of the filmformer layer inside the tube, as well as a longer period between measurements compared to a smooth tube, thereby improving the performance characteristics of the flowmeter.

Table 5. Results of the study of smooth tubes.

No.	Time τ, min		Resistance R in kΩ between contacts 9 and 10 (see Fig.2) for the measuring tube		
			No. 1	No. 2	No. 3
1	0		9275.7	7212.2	
2	After passing from the beginning of the experiment	of the 1st film	990.0	802.5	856.7
3		2nd film	1005.6	754.7	823.3
4		3rd film	1038.4	802.5	802.5
5		4th film	1073.3	792.5	802.5
6		5th film	1073.3	754.7	782.7
7	1		1110.7	845.3	763.8
8	10		1615.0	1537.6	1193.7
9	20		2156.7	2397.4	1656.7
10	30		2490.0	3085.2	2021.3
11	40		3085.2	3601.1	2397.4
12	50		3411.1	4323.3	2698.3
13	60		3601.1	4632.8	3085.2
14	70		4052.5	5406.7	3411.1
15	80		4323.3	5899.1	3601.1
16	90		4323.3	7212.2	
17	98		4632.9		

Table 6. Results of the study of matte tubes.

No.	Time τ, min		Resistance R in kΩ between contacts 9 and 10 (see Fig.2) for the measuring tube			
			No. 1	No. 2	No. 3	No. 1
1	0		7212.2	6490.0	5899.1	5899.1
2	After passing from the beginning of the experiment	of the 1st film	823.3	745.8	823.3	621.1
3		2nd film	802.5	773.1	823.3	667.1
4		3rd film	745.8	792.5	868.4	660.1
5		4th film	728.6	802.5	868.4	660.1
6		5th film	728.6	823.3	868.4	646.6
7	1			845.3	868.4	696.5
8	10		960.1	1150.7	1091.7	1073.3
9	20		1150.7	1372.9	1264.5	1344.2
10	30		1344.2	1501.6	1403.0	1537.6
11	40		1467.3	1656.7	1537.6	1746.8
12	50		1537.6	1795.6	1615.0	1847.1
13	60		1656.7	1901.8	1746.7	2021.3
14	70		1746.8	2021.3	1795.6	2156.7
15	80		1795.6	2156.7	1847.1	2231.4
16	90		1901.7	2231.4	1901.8	2397.4
17	100		1959.7	2311.4	1959.7	2490.0
18	110		2021.3	2397.4	1959.7	2590.0
19	120		2156.7	2490.0	2021.3	2698.3
20	130		2231.4	2590.0	2086.7	2816.1
21	140		2311.4	2590.0	2156.7	2816.1
22	150		2397.4	2698.3	2231.4	
23	160		2397.4	2698.3		
24	170		2490.0	2816.1		
25	180		2590.0	2944.5		
26	190		2590.0	2944.5		
27	200		2698.3	2944.5		
28	210		2698.3	3085.2		
29	220		2816.1	3085.2		

Another comparative study of smooth and matte tubes was conducted with another solution. The solution used as a film-forming liquid was ethylene glycol + synthanol (17 %) + aqueous solution of salt. The length of measuring tubes was $l = 390$ mm, and the diameter of measuring tubes was $d = 20$ mm. The results of measuring the electrical resistance R of the film-forming liquid layer inside the measuring tubes (smooth and matte) are shown in Fig.3.

It is of interest to note that after three days the layer of the film-forming liquid inside the matte tube remained and inside the smooth tube it completely dried out ($R = \infty$).
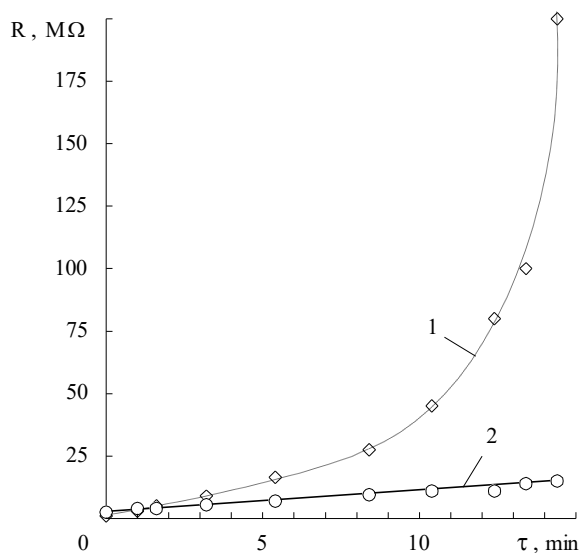

Fig.3. Electrical resistance R of the film-forming liquid layer (ethylene glycol + 17 % synthanol + aqueous salt solution) inside the measuring tubes vs. time τ: 1 – smooth; 2 – matte.

The conducted experimental studies of the smooth and matte tubes confirmed that the thickness of the filmformer layer depends on the properties of the inner surface of the flowmeter measuring tube. The matte surface improves its wettability, and therefore, ensures the stability and constancy of the shape and geometric dimensions of the filmformer layer, which increases the accuracy and reliability of gas flow measurement by the film flowmeter, as well as improves the operational characteristics of the device.

5. Conclusion

The choice of the composition of the film-forming liquid and the measuring tube has been justified for the improvement of the metrological and technical characteristics of the film flowmeter. Furthermore, using a film generator, a device for removing destroyed films, automatic film position locks and automatic flow calculation taking into account the state of the gas, using temperature stabilization and smoothing of pressure pulses will enable creating a high-precision device suitable for metrological support of industrial flowmeters and calibration of gas meters. The total error of such film flowmeter depends on its design, the quality of calibration, and the properties of the gas under study. With the implementation of the above measures, the measurement error of the film flowmeter may not exceed 0.1 %.

References

[1]   Kremlevskyi, P.P. (2015). Flowmeters and counters of the amount of substances. Book 2: handbook. 5th ed. St. Peterburg: Politekhnika, 412 p. (in Russian)

[2]   Levy, A. (1964). The accuracy of the bubble meter method for gas flow measurements. *Journal of Scientific Instruments*, 41(7), 449–453. https://doi.org/10.1088/0950-7671/41/7/309

[3]   Schone, G. (1980) Seifenfilmstromungsmesser mit digitaler Anzeige der Stromungsgeschwindigkeit. GDR Patent No. 143 823.

[4]   Stonestrom, D.A. (1990) Soap film flowmeter device for measuring gas flow rates. US Patent No. 4,914,955.

[5]   Danko, A.F., Ignashkin, I.S. (1997) Film flowmeter. Ukraine Patent No. 13107. (in Ukrainian)

[6]   Pistun, Ye.P., Stasiuk, I.D. (1998) Method of assessing the volume of the measuring tube of the film flowmeter. Ukraine Patent No. 23852. (in Ukrainian)

[7] Hill, S.L. (1987) Soap film gas flowmeter. US Patent No. 4,691,577.

[8] Small, P. (1982) Bubble flowmeter. UK Patent No. 2,092,742 A.

[9] Patterson, D. (1989) Soap film flowmeter. US Patent No. 4,879,907.

[10] Lashkari, S., Kruczek, B. (2008). Development of a fully automated soap flowmeter for micro flow measurements. *Flow Measurement and Instrumentation*, 19(6), 397–403. https://doi.org/10.1016/j.flowmeasinst.2008.08.001

[11] Fursenko, R.V., Odintsov, E.S. (2022). A novel concept of automatic soap flowmeter with bubble detection by closing an electrical circuit. *Flow Measurement and Instrumentation*, 85, 102165. https://doi.org/10.1016/j.flowmeasinst.2022.102165

[12] Odintsov, E.S., Fursenko, R.V., Chusov, D.V. (2020) Filmbubble flowmeter. RF Patent No. 2,723,905.

[13] Zhikhua, L., Zhitsyan, Z., Zhen, L., Li, S. (2022) Electronic film flowmeter. CN Patent No. 217637486 U.

[14] Pistun, Ye.P., Tepliukh, Z.M., Stasiuk, I.D. (1982). Determination of flow characteristics of throttle elements. *Automation and instrumentation in the oil refining and petrochemical industries*. (in Russian)

[15] Tepliukh, Z.M., Parneta, O.Z. (1999). Working fluid of the film flowmeter. *Bulletin of Lviv Polytechnic State University, Thermal Power Engineering. Environmental Engineering. Automation*, 378, 73–76. (in Ukrainian)

[16] Tepliukh, Z.M., Parneta, O.Z. (2000). The influence of high-molecular admixtures on the quality of films in micro flowmeters. *Bulletin of Lviv Polytechnic National University, Thermal Power Engineering. Environmental Engineering. Automation*, 404, 103–105. (in Ukrainian)

[17] Kruhliakov, P.M., Ekserova, D.R. (1990). Foam and foam films. Moscow: Khimiia. (in Russian)

[18] Parneta, O.Z., Tepliukh, Z.M. (2008). Influence of gas transfusion on the accuracy of flow measurement using a film flowmeter. *Bulletin of Lviv Polytechnic National University, Thermal Power Engineering. Environmental Engineering. Automation*, 617, 179–183. (in Ukrainian)

[19] Poling, B.E., Prausnitz, J.M. (2000). The properties of gases and liquids. 5th ed. McGraw Hill, 803 p.

[20] Elliot, J.R. (2023). The properties of gases and liquids. 6th ed. McGraw Hill, 784 p.

[21] Parneta, O.Z., Tepliukh, Z.M. (2010). Influence of the measuring tube surface on the characteristics of a film flowmeter. *Bulletin of Lviv Polytechnic National University, Thermal Power Engineering. Environmental Engineering. Automation*, 677, 134–138. (in Ukrainian)

Заходи з покращення метрологічних і технічних характеристик плівкового витратоміра газів

Оксана Парнета, Іван Стасюк, Ігор Ділай, Ігор Демків

Національний університет «Львівська політехніка», вул. С. Бандери, 12 , Львів, 79013, Україна

Анотація

Проблеми вимірювання малих витрат (зокрема підвищення точності та розширення діапазону вимірювання) є актуальними як в сучасних технологіях, так і в експериментальних дослідженнях. Похибка плівкового витратоміра залежить від його виконання, якості градуювання, а також властивостей досліджуваного газу та плівкоутворюючої рідини. У роботі розглянуто питання оптимізації складу плівкоутворюючої рідини плівкового витратоміра з метою підвищення точності вимірювання мікровитрат газів. Досліджена можливість збільшення тривалості існування плівок за допомогою введення у плівкоутворюючу рідину стабілізатора – високомолекулярної домішки (полімера) поліакриламіду (ПАА). Досліджено властивості плівок, утворених з різних розчинів, одержано оптимальний склад плівкоутворювача з використанням ПАА і запропоновано використовувати його у плівкових витратомірах з метою підвищення точності та надійності вимірювання мікровитрат газів. В роботі також розглянуто механізм трансфузії газів через плівку та оцінено його вплив на точність вимірювання витрати, а також вказано рекомендації щодо зменшення (усунення) похибки внаслідок впливу трансфузії. Досліджено вплив шару плівкоутворювача всередині мірної трубки та умови його існування, розглянуто властивості внутрішньої поверхні мірної трубки, зокрема матування внутрішньої поверхні трубки.

Ключові слова: плівковий витратомір; мірна трубка; вимірювання витрати газу; мильний витратомір; плівкоутворююча рідина.