**Intelligent Installation for Measuring Small and Micro Gas**

**Flow Rates Based on a Film Flowmeter**

Ivan Stasiuk1, Ihor Dilai2, Solomiia Markiv3, Valentyn Shevchuk4, Oksana Parneta5

1. Department of Automation and Computer-Integrated Technologies, Lviv Polytechnic National University, UKRAINE, Lviv, 5 Ustiyanovycha Str., E-mail: ivan.d.stasiuk@lpnu.ua
2. Department of Automation and Computer-Integrated Technologies, Lviv Polytechnic National University, UKRAINE, Lviv, 5 Ustiyanovycha Str., E-Mail: divlv@ukr.net
3. Department of Automation and Computer-Integrated Technologies, Lviv Polytechnic National University, UKRAINE, Lviv, 5 Ustiyanovycha Str., E-mail: solomiia.markiv.av.2022@lpnu.ua
4. Department of Automation and Computer-Integrated Technologies, Lviv Polytechnic National University, UKRAINE, Lviv, 5 Ustiyanovycha Str., E-mail: valentyn.v.shevchuk@lpnu.ua
5. Department of Automation and Computer-Integrated Technologies, Lviv Polytechnic National University, UKRAINE, Lviv, 5 Ustiyanovycha Str., E-mail: ozpatxp@ukr.net

***Abstract – The causes of errors in measuring small gas flow rates by the film method are analyzed and measures to minimize them are proposed. As a result, an intelligent installation for measuring gas flow rates in the range of 0…25.0·10-6 m3/s with an error of 0.25% was developed. The system designed for calibration of high-precision flow meters used in automated control systems for modern technological processes.***

Keywords – intelligent flow measuring installation; small gas flow measurement; measuring pipe; film flowmeter.

Introduction

The effectiveness of automated process control systems significantly depends on the amount of primary information about the course of such processes and is determined by the level of development of control and measuring equipment [1-3]. Thus, in the construction of automated control systems for modern technological processes that require small and micro gas flow rate measurement devices [4-9], as well as for metrological support of gas analytical equipment, in particular, gas-dynamic synthesizers of gas mixtures [10-13] and research [14-18], one of the main problems is the lack of high-precision micro (0…3.0·10-6 m3/s in pipes with a diameter of 1…5 mm) and small (3.0·10-6…3.0·10-3 m3/s in pipes with a diameter of 5…10 mm) gas flow rate measurement devices [19-21].

The need to measure such gas flows usually arises in the latest technologies, in particular, in the production of fiber-optic cables [22], the manufacture of integrated circuits and microelectronic devices [23], as well as in vacuum engineering processes, in medicine, and in metrological work [6, 8, 17]. Therefore, the development of intelligent high-precision flowmeters for the mentioned flow ranges with stable metrological characteristics is an essential task.

1. Film flowmeters of tiny and micro flow rates of gases

One of the most promising methods of measuring small and micro flow rates of gases is the film method, on the basis of which a number of film flowmeters (FFM) are built [24-26]. The process of measuring small and micro flow rates of gases using FFM is accompanied by the influence of various factors that lead to errors. The occurrence of additional errors, in addition to errors in determining the volume of the calibrated section of the measuring pipe (MP) and measuring the time of passage of the film through this volume, is caused by changes in atmospheric pressure and temperature of the measured gas flow [19-21]. Elimination (minimization) of such effects makes it possible to significantly reduce the overall measurement error.

The schematic diagram of the FFM, traditionally used to measure such gas flow rates, is shown in Fig. 1 a [21]. The FFM contains the measuring pipe 2 fixed on the tripod 1 with the inlet element 3 for supplying the measured gas and the inlet element 4 for supplying a surfactant solution, a chronometer 5 and the elastic reservoir 6 with a surfactant solution 7 for forming a film. The flow of the measured gas moves the formed film along the inner wetted surface of the MP. Two marks (lower 8 and upper 9) on the MP limit its calibrated area (volume), the time of film passage between which is measured by a chronometer.

The measurement of gas volumetric flow rate using a FFM is to directly determining the time interval for the film to displace a portion of gas from the calibrated volume, and the value of the volumetric flow rate is determined by the formula [19, 21]

, (1)

where *Q* – volumetric flow rate; *V* – calibrated volume of the МP; τ – measured time of film movement between the marks of the calibrated volume of the MP.

 

Fig. 1. Schematic diagram of a film flow meter:

1 – tripod; 2 – measuring pipe; 3 and 4 – inlet element for supplying the controlled gas and surfactant solution; 5 – chronometer;

a) basic design: 6 – elastic reservoir; 7 – surfactant solution; 8 and 9 – marks that limit the calibrated volume of the MP;

b) improved automated design: 6 – automated film former; 7 – surfactant solution reservoir;
8 – surfactant solution; 9 and 10 – optoelectric level indicators; 11 – control device;

12 – rotary valve; 13 – electromagnetic drive

The main error in gas flow measurement using FFM usually does not exceed 1 % [7, 19]. However, due to the inconsistency of the design and application of the FFM with the measurement conditions, additional flow measurement errors occur. For example, as our research has shown, only due to the humidification of the monitored gas with water vapor as a surfactant solvent, the measurement error can reach 3 %.

To form a film in the FFM, aqueous solutions of liquid soap or ammonium oleate are usually used. To prevent foam formation, a silicone emulsion is added to the surfactant solution [19]. The analysis of the operation of such FFM has shown that water evaporates from such a surfactant solution in the MP, as a result of which the volume of controlled gas in the MP increases. This leads to an additional systematic error in gas flow measurement. For example, at atmospheric pressure and a gas temperature of 25 °C, its humidification with water vapor to a relative humidity of 65 % leads to an increase in volume by 2.15 %, and in the case of gas humidification to full saturation – by 3.3 %. To reduce the impact of this factor, liquids with a higher boiling point than water should be used instead of water as a surfactant solvent. For example, for ethylene glycol with a boiling point of 190 °C, the saturated vapor pressure at room temperature does not exceed 100 Pa, so that even when the gas is fully saturated with ethylene glycol vapor, the increase in gas volume at atmospheric pressure and a temperature of 25 °C does not exceed 0.1 % [27, 28].

It should also be noted that some gases react with the surfactant solution. For example, carbon dioxide reacts with an aqueous soap solution, resulting in a decrease in the effective volume of the gas. This also increases the flow measurement error. To eliminate the influence of this factor, it is necessary to use solutions that do not react with the controlled gases. The most versatile solutions are neutral surfactant solutions, for example, solutions of oxyethylated alcohols.

Our research has shown that the following factors mainly affect the measurement error of a film flowmeter:

* accuracy of determining the volume of the calibrated MP section;
* accuracy of measuring the time of passage of the film through this area;
* flow rate measurement conditions (atmospheric pressure and temperature of gas and environment);
* speed of the film movement;
* gas flow through the film;
* physical and chemical properties of both controlled gases and used surfactants and their solvents.

Thus, the aim of the work is to develop measures to improve the accuracy of gas flow measurement by the film method and to create metrological support for high-precision measurement of small and micro flow rates of gases used in innovative process control systems.

As a result of the analysis of the above factors and their influence on the components of the flow measurement errors, specific recommendations for the construction of high-precision flow meters and the creation of an intelligent installation for measuring small and micro flow rates of gases have been developed.

It is recommended to use liquids with a boiling point of at least 190 °C, in particular, ethylene glycol, as a solvent of the surfactant in the FFM, and neutral surfactants, such as oxyethylated alcohols, as a film forming agent.

It is advisable to choose the length of the MP of the film flowmeter within 50...80 cm, provided that the flowmeter is compact in design. To increase the accuracy of determining the volume of the calibrated MP section, it is advisable to make the sections with the limiting marks narrower. To prevent film rupture when moving from a narrower to a wider MP section and vice versa, the ratio of the diameters of its middle expanded and extreme narrowed sections should not exceed 3. To ensure smooth movement of the film along the calibrated section of the measuring pipe and to keep it in a horizontal position, the transitions between the expanded and narrowed sections of the measuring pipe should be made in the form of cut cones with an inclination angle of at least 60 º, which are connected to the cylindrical surfaces of the measuring pipe by means of toroidal surfaces.

Taking into account the proposed recommendations and research a high-precision automated film flowmeter was developed. During the development of the installation, all the technical requirements and application features of the system were taken into account. The schematic diagram of which is shown in Fig. 1 b.

The calibrated section of the MP of the developed FFM is limited by optoelectric level indicators 9 and 10 connected through the control device 11 to the chronometer 5, which minimizes the error in measuring the time of passage of the graduated volume by the film between the limiting marks. In addition, in this FFM, the inlet element 4 for supplying the surfactant solution to the MP before the inlet element 3 for supplying gas to it is equipped with a rotary valve 12 with an electromagnetic drive 13 connected to the control device 11, which ensures a hermetic separation of the container 7 with the surfactant solution from the controlled gas flow during the measurement of its flow. This design reduces the component of the measurement error arising from the evaporation of the surfactant solvent.

In addition, the peculiarity of the developed FFM is that the volume of the calibrated section of the MP is determined taking into account the adhesion of the surfactant solution on its inner surface, which minimizes the systematic component of the flow measurement error created by this factor.

To minimize the effect on the error of the film flowmeter of gas transfusion through the film when measuring the flow rate of air or gases with a density greater than the density of air, such gases must be supplied to the MP from below. In this case, the film moves from the lower optoelectric indicator of level 9 to the upper level 10. Conversely, when measuring the flow rate of gases with a density lower than the density of air, it is necessary to supply gas to the measuring pipe from above and the film then moves from the upper optoelectric indicator of level 10 to the lower level 9.

All of the factors discussed above determine the systematic component of the film flowmeter measurement error. This component of the film flowmeter error is mainly influenced by changes in atmospheric pressure, temperature of the controlled gas, and the volume of the calibrated measuring pipe section.

The random component of the FFM measurement error is mainly determined by the instability of the measured flow. Our studies have shown that the random component of the error due to the instability of the measured flow can reach several percent. Therefore, in order to reduce the measurement error of the FFM and its random component, it is necessary to stabilize the measured gas flow.

1. Intelligent Instalation for Measuring Small and Micro GasFlow Rates Based on a Film Flowmeter

On the basis of the automated FFM described above and taking into account the requirements for gas flow stabilization, an intelligent installation for measuring small and micro flow rates of gases was developed, the block diagram of which is shown in Fig. 2. The installation includes an automated flow meter placed in a closed enclosure with a temperature stabilization system, as well as a microprocessor device for monitoring and controlling the operation of the installation with displaying the flow measurement results [29]. The setup also contains a gas temperature sensor, a barometer, a gas flow stabilizer, and a section for installing the flow meter under test. The installation is intelligent, since the obtained flow measurement result takes into account, in addition to the main quantities – the volume of the calibrated MP section and the time of passage of the film through this section, and gas temperature and atmospheric pressure, i.e. parameters of the controlled gas state.



Fig. 2. Block diagram of an intelligent unit for measuring

of small and micro flow rates of gases:

1 – automated FFM; 2 – gas temperature sensor; 3 – barometer; 4 – temperature stabilization system in the installation housing; 5 – installation housing; 6 – microprocessor control and management device; 6 – device for displaying flow measurement results;

8 – gas flow stabilizer; 9 – site for installation of the flowmeter under study;

10 – the flow meter under test

Thus, the result of measuring the volumetric flow rate of gas reduced to normal conditions is determined using the microprocessor device of the intelligent flowmeter according to the following formula

 (2)

where *Q* – the volume gas flow rate reduced to normal measurement conditions; *V* – the volume of the calibrated MP section; τ – the time of movement of the film along the calibrated MP section by the controlled gas; *Pb* – the atmospheric pressure; *Tc* – the temperature of the controlled gas; *Тn*=293.15 ºС – the normal temperature; *Рn* = 101325 Pa – the normal pressure.

The developed intelligent installation provides measurement of small and micro flow rates of gases in the range of 0…25.0·10-6 m3/s with an error of 0.25 %. The installation is designed for calibration and verification of high-precision measuring instruments for small and micro flow rates of gases.

1. Conclusions

Thus, as a result of the technical implementation of measures to eliminate (reduce) the impact of the identified causes of systematic and random components of the measurement error of small and micro gas flow rates, a high-precision intelligent installation based on the film measurement method was developed. The developed installation, due to the determination of the parameters of the state of the controlled gas and the environment (external temperature and atmospheric pressure), as well as due to the stabilization of the gas flow in the process of measuring its flow rate, minimized the components of the flow measurement error, and thus increased the accuracy of measurements. The installation provides measurement of small and micro flow rates of gases in the range from 0…25.0·10-6 m3/s with an error not exceeding 0.25 %

Further promising areas of research in film flowmeter include, in particular, expanding the range of industrial gas flow measurement, improving systems for measuring the time of film passage through the calibrated volume of measuring pipe, as well as thermostating and calibration. Such research will help to improve both metrological and operational characteristics of the film flowmeter, which will further meet the growing requirements for flow measurement devices in the latest technological processes. This will also help reduce maintenance and operating costs, which is an important factor for modern industry.

References

[1] The 12th international Gas Analysis Symposium & Exhibition (GAS 2024), Porte de Versailles Paris (France), 2024. URL: https://www.gasanalysisevent.com/images/gasanalysis/docs/

GAS2024-Fullprogramme.pdf

[2] GAS Analysis 2022 Conference (GAS 2022), Paris (France), 2022.

URL: https://www.gasanalysisevent.com/programme/2022-programme

[3] Arseniev, D. G., & Aouf, N. (2023). Cyber-Physical Systems and Control II. Springer, 682 p.

URL: https://link.springer.com/book/10.1007/978-3-031-20875-1

[4] Teplukh, Z., & Dilai, I., & Stasiuk, I., & Tykhan, M., & Kubara, I.-R., (2018). Design of linear capillary measuring transducers for low gas flow rates. Eastern-European Journal of Enterprise Technologies, vol. 6, issue 5 (96), pp.25-32. DOI: 10.15587/1729-4061.2018.150526.

1. Topolnicki, J., & Kudasik, M., & Skoczylas, N., & Sobczyk, J., (2009). Low cost capillary flow meter. Sensors and Actuators A: Physical, vol. 152, issue 2, pp. 146-150.
DOI: 10.1016/j.sna.2009.03.023

[6] West, T., & Photiou, A., (2018). Measurement of gas volume and gas flow. Anaesthesia & Intensive Care Medicine, vol. 19, issue 4, pp.183-188. DOI: 10.1016/j.mpaic.2018.02.004.

[7] [Lashkari, S.,](https://www.scopus.com/authid/detail.uri?authorId=14031831600) & Kruczek, B., (2008). Development of a fully automated soap flowmeter for micro flow measurements. [Flow Measurement and Instrumentation](https://www.scopus.com/authid/detail.uri?authorId=14031831600#disabled), vol.19, issue 6,
pp. 397-403. DOI: [10.1016/j.flowmeasinst.2008.08.001](https://doi.org/10.1016/j.flowmeasinst.2008.08.001).

[8] Henderson, M. A., & Runcie, C. (2017). Gas, tubes and flow. Anaesthesia & Intensive Care Medicine, vol. 18, issue 4, pp. 180-184. DOI: 10.1016/j.mpaic.2017.01.009

[9] OOO-Monitoring. Gas flow meters "STREAM" [Online].
Available: https://www.ooo-monitoring.ru/products/equip/gasflow/potok/

[10] [Dilay, I.](https://www.scopus.com/authid/detail.uri?authorId=57192819863), & [Teplukh, Z.](https://www.scopus.com/authid/detail.uri?authorId=6506204298), & [Tykhan, M.](https://www.scopus.com/authid/detail.uri?authorId=55699982500), & [Stasiuk, I.](https://www.scopus.com/authid/detail.uri?authorId=57202004588), & [Kubara, I.-R.](https://www.scopus.com/authid/detail.uri?authorId=57192821066), (2017). [Effect of external pressures in dynamic gas mixers](https://www.scopus.com/record/display.uri?eid=2-s2.0-85028524576&origin=resultslist&sort=plf-f). [Eastern-European Journal of Enterprise Technologies](https://www.scopus.com/sourceid/21100450083?origin=resultslist), 4(5-88), pp. 59-65. DOI: [10.15587/1729-4061.2017.26256](https://doi.org/10.15587/1729-4061.2017.26256).

[11] Haerri, H.-P., & Mace, T., & Walden, J., & Pascale, C., & Niederhauser, B., & Wirtz, K. et. al., (2017). Dilution and permeation standards for the generation of NO, NO2 and SO2 calibration gas mixtures. Measurement Science and Technology, vol. 28, issue 3, 035801 (17 pp). DOI: 10.1088/1361-6501/aa543d

[12] Helwig, N., & Schüler, M., & Bur, C., & Schutze, A., & Sauerwald, T., (2014). Gas mixing apparatus for automated gas sensor characterization. Measurement Science and Technology, vol. 25, issue 5, 055903 (9 pp). DOI: 10.1088/0957-0233/25/5/055903

[13] Słomińska, M., & Konieczka, P., & Namieśnik, J., (2014). New developments in preparation and use of standard gas mixture. TrAC Trends in Analytical Chemistry, vol. 62, pp.135–143. DOI: 10.1016/j.trac.2014.07.013.

[14] [Dilay, I.](https://www.scopus.com/authid/detail.uri?authorId=57192819863), & [Teplukh, Z.](https://www.scopus.com/authid/detail.uri?authorId=6506204298), & [Brylyns'kyy, R.](https://www.scopus.com/authid/detail.uri?authorId=57221094729), & [Kubara, I.-R.](https://www.scopus.com/authid/detail.uri?authorId=57192821066), (2016). Development of gas dynamic linear systems for setting low pressures. Eastern-European Journal of Enterprise Technologies, 4(7-82), pp. 30-36. DOI: 10.15587/1729-4061.2016.75231

[15] [Dilay, I.](https://www.scopus.com/authid/detail.uri?authorId=57192819863), & [Teplukh, Z.](https://www.scopus.com/authid/detail.uri?authorId=57553362100), & [Vashkurak, Y.](https://www.scopus.com/authid/detail.uri?authorId=57214991811), (2014). Basic throttling schemes of gas mixture synthesis systems. Eastern-European Journal of Enterprise Technologies, 4(8), pp. 39-45. DOI: 10.15587/1729-4061.2014.26257

[16] Takami, T., & Nishimoto, K., & Goto, T., & Ogawa, S., & Iwata, F., & Takakuwa, Y., (2016). Argon gas flow through glass nanopipette. Japanese Journal of Applied Physics, vol. 55, issue 12, 125202 (5pp.). DOI: 10.7567/jjap.55.125202.

[17] Barbe, J., & Boineau, F, & Macé, T., & Otal, P., (2015). Development of a gas micro-flow transfer standard. Flow Measurement and Instrumentation, vol. 44, pp.43-50.
DOI: 10.1016/j.flowmeasinst.2014.11.011.

[18] [Dilay, I.](https://www.scopus.com/authid/detail.uri?authorId=57192819863), & [Teplukh, Z.](https://www.scopus.com/authid/detail.uri?authorId=6506204298), (2014). Development of throttle selector of significantly different pressures for gas-dynamic tools. Eastern-European Journal of Enterprise Technologies, 6(7),
pp. 28-33. DOI:10.15587/1729-4061.2014.31390

[19] Kremlevskyi, P. P., (2015). Flowmeters and counters of the amount of substances. Book. 2: handbook, (5th ed.). St.Petersburg: Politekhnika, 412 p.
URL: https://www.rosmedlib.ru/book/ISBN5732507094.html

[20] Liptak, B. G., (2022). Flow Measurement, (1st ed.). CRC Press, 222 p.
URL: https://www.routledge.com/Flow-Measurement/Liptak/p/book/9780801983863

[21] Levy, A., (1964). The accuracy of the bubble meter method for gas flow measurements.
[Journal of Scientific Instruments](https://iopscience.iop.org/journal/0950-7671), vol. 41, issue 7, pp. 449-453.
DOI: 10.1088/0950-7671/41/7/309

[22] [Udd](https://www.amazon.com/s/ref%3Ddp_byline_sr_ebooks_1?ie=UTF8&field-author=Eric+Udd&text=Eric+Udd&sort=relevancerank&search-alias=digital-text), E., (2024). Fiber Optic Sensors: An Introduction for Engineers and Scientists (3rd ed.).  Wiley, 624 p. URL: https://www.ravenbookstore.com/book/9781119678786

[23] Jackson, R. G., (2019). Novel Sensors and sensing. CRC Press Taylor & Francis Group, 310 p. URL: www.taylorfrancis.com/books/mono/10.1201/9780429138348/novel-sensors-sensing-roger-jackson

[24] 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, vol.85, 102165 (11 pp.). DOI: 10.1016/j.flowmeasinst.2022.102165.

[25] Odintsov, E. S., & Fursenko, R. V., & Chusov, D. V., (Jun. 2020). Filmbubble flowmeter, RF Patent 2 723 905.

[26] Zhikhua, L., & Zhitsyan, Z., & Zhen, L., & Li, S., (Oct. 2022). Electronic film flowmeter, CN Patent 217637486 U. URL:https://patents.google.com/patent/CN217637486U/en?oq=CN%C2%A0Patent%C2%A0217637486+U

[27] [Poling](https://www.amazon.com/Bruce-E-Poling/e/B001IXRXMG/ref%3Ddp_byline_cont_ebooks_1), & Bruce E., [& Prausnitz](https://www.amazon.com/s/ref%3Ddp_byline_sr_ebooks_2?ie=UTF8&field-author=John+M.+Prausnitz&text=John+M.+Prausnitz&sort=relevancerank&search-alias=digital-text), & John M., (2000). The Properties of Gases and Liquids (5th ed.). McGraw Hill, 803 p. URL: www.ebooks.com/en-us/book/300463/the-properties-of-gases-and-liquids-5e/bruce-e-poling/

[28] [Elliott](https://www.amazon.sg/s/ref%3Ddp_byline_sr_book_1?ie=UTF8&field-author=J.+Richard+Elliott&search-alias=books), J. Richard, (2023). The Properties of Gases and Liquids (6th ed.). McGraw Hill, 784 p. URL:www.mhprofessional.com/the-properties-of-gases-and-liquids-sixth-edition-9781260116342-usa

[29] Monk, S., (2022). Raspberry Pi Cookbook: Software and Hardware Problems and Solutions, (4th ed.). O'Reilly Media, 621 p. URL: [www.oreilly.com/library/view/raspberry-pi-cookbook/9781098130916/](http://www.oreilly.com/library/view/raspberry-pi-cookbook/9781098130916/)