

**PHYSICAL DEVICES FOR ECOLOGY,
MEDICINE, BIOLOGY**

WIDE-RANGE ACOUSTIC ANALYZER OF TWO-COMPONENT GAS MIXTURE

©2025 V. N. Alferov*, D. A. Vasiliev

A.A. Logunov Institute of High Energy Physics

National Research Center “Kurchatov Institute”

Russia, Protvino, Moscow region

**e-mail:Vladimir.Alferov@ihep.ru*

Received May 27, 2024

Revised September 13, 2024

Accepted October 14, 2024

Abstract. A sensor for analyzing the composition of a binary gas mixture using an acoustic resonator is described based on the dependence of the speed of sound in a gas on its molecular weight. To analyze the composition of the mixture, one of the gases in pure form must be available. In this case, the measurement error is no worse than 10-4. A mixture with a known composition can also be used as a reference.

DOI: 10.31857/S00328162250101e6

1. INTRODUCTION

Acoustic analyzers are generally designed to determine the concentration of impurities in the main gas. The operation of acoustic analyzers is based on the use of the dependence of the speed of sound on the molecular weight of the gas. Speed of sound v is calculated using the following formula:

$$v = \sqrt{\gamma RT/M},$$

where γ is the adiabatic index ($\gamma = C_p/C_V$), C_p – heat capacity of gas at constant pressure, $C_V = C_p - R$ – heat capacity of gas at constant volume, M – molecular mass of gas, R – universal gas constant, T [K] – gas temperature.

When detecting small amounts of impurity gas to the main gas, a simplified calculation method can be used. If we know the molecular mass of the main and impurity gases, then the speed of sound in the main gas in the presence of impurity can be represented in the first approximation by the following formula:

$$C_x = \sqrt{\frac{RT}{x\left(\frac{M}{\gamma}\right)_{np} + (1-x)\left(\frac{M}{\gamma}\right)_{och}}} ,$$

where χ is the relative concentration of the impurity.

In an analyzer based on an acoustic resonator, the resonance frequency is proportional to the speed of sound, the appearance of an impurity causes a measurable frequency deviation.

2. ANALYZER CONSTRUCTION

The analyzer design largely replicates the structure of a previously developed hydrogen presence sensor in the atmosphere of a target station, developed by NRC Kurchatov Institute–IHEP, for the C-70 cyclotron accelerator, which ensures the production of medical isotopes [1]. It is based on a patented half-wave resonator with a diameter slightly smaller than its length, a Q-factor of about 300 in air, and diffusion filling [2]. The analyzer is schematically shown in Fig. 1.

Fig. 1. Block diagram of the acoustic analyzer

For diffusion filling, there are holes 2 with a diameter of about 3 mm in the middle of the height at the antinode of velocity. The emitter 3 and microphone 4 are installed at the ends of the resonator, which communicate with the resonator cavity through holes 5 with a diameter of about 2 mm.

The emitter and microphone are included in the feedback circuit of the auto-generator 6, implemented on the VCO 1561GG1 chip. The temperature is monitored by two platinum sensors 7. The auto-generator is excited at a frequency of about 5 kHz in an atmosphere of pure dry air, the frequency is measured once per second for 0.1 s in the measurement and control unit 9. The frequency of the measurement quartz generator is regularly checked by applying a reference frequency of known value to the measuring channel, implemented on a binary counter chip with a quartz resonator; a correct result is an indication of properly functioning electronics.

Under stable conditions of temperature and gas composition, the instability of the resonance frequency readings does not exceed 10^{-5} .

From the above formula for the speed of sound in gas, it follows that if we know the measured resonant frequency of one of two pure gases with known molecular weight and adiabatic constant at a known temperature, then we can calculate the resonant frequency of any mixture of these gases at any temperature.

When measuring in gases with a small proportion of impurities (a few percent), the accuracy of tuning the self-oscillator frequency to the resonance frequency is not of great importance; the relative content of the impurity equals twice the relative change in the self-oscillator frequency in relation to

the frequency in an atmosphere of pure base gas. In other cases, to determine the proportion of impurity, it is necessary to know the molecular mass and the adiabatic constant of the gas mixture, characterized by the resonant frequency of the resonator, which also depends on temperature.

The problem of measuring the resonant frequency is that the measured frequency of the self-oscillator on the 1561GG1 microchip used in the analyzer coincides with the resonant frequency of the resonator only if it is the natural frequency of the self-oscillator. For a heavier gas (taking into account the adiabatic constant), it is higher, and for a lighter one, it is lower than the resonant frequency. This is illustrated in Fig. 2 for a mixture of air with Freon 22.

Fig. 2. Resonant frequency of the resonator F_{res} and frequency of the self-oscillator F_{so} .

Thus, to calculate the molecular mass of a gas mixture, a three-dimensional picture of the dependencies of the resonator's resonant frequency on the self-oscillator frequency at different temperatures is needed. Temperature dependencies are recorded in a climate chamber with gas supplied from outside. The resonant frequency is determined by the maximum signal from the resonator when it is excited by an external generator and controlled by the device's electronics. The second method for determining the resonant frequency involves adjusting the natural frequency of the self-oscillator so that the frequency does not change when the resonator is connected. The tuning error by both methods can be estimated at ± 1 Hz.

The approximation of data is facilitated by the following circumstances. From the formula for the speed of sound in a gas and, accordingly, the resonant frequency of the resonator, it follows that for any molecular mass of gas, the product $F_{\text{res}} \cdot \sqrt{M/\gamma}$ does not depend on the molecular weight; it depends only on temperature (Fig. 3). Similarly, the quotient of the resonant frequency divided by the square root of the absolute temperature $F_{\text{res}} / \sqrt{T}$ does not depend on temperature. Taking this into account, the error in determining the resonant frequency can be reduced to fractions of Hz, and, accordingly, the error in determining the molecular weight will decrease to hundredths of a percent.

Fig 3. Dependence of resonant frequency on $\sqrt{M/\gamma}$ at different temperatures

The phase capture range of the PLL of the 1561GG1 chip is $\pm 90^\circ$ between output and input signals. Therefore, it is advisable to choose the natural frequency of the oscillator in the middle between the resonant frequencies of pure gases, as shown in Fig. 2.

It is important to use an emitter with a low inductance of the excitation coil, for example, an in-ear headphone emitter, since inductance is what limits the frequency range of the oscillator. This configuration of the device allowed measuring the molecular weight of mixtures from Freon 22 ($M = 86.4$) to a 50-percent mixture of air with helium. The resulting measurement error was 0.025%.

The device communicates with a computer via RS-232 or RS-485 lines. The external appearance (the same as the hydrogen sensor from work [1]) is shown in Fig. 4.

Fig. 4. External view of the gas analyzer.

Let us compare the described device with sensors analyzing various gas mixtures based on other physical principles.

Among the most accurate methods for determining the composition of a gas mixture, chromatography and spectroscopy are the most common. For example, the gas chromatograph RD 34.46.303-98 [3] provides a detection limit for gases in oil not higher than 0.00005% for acetylene and 0.0001% for methane, ethylene, and ethane.

Fourier spectrometers (FSM) in the IR range [3] can also be effectively used for multicomponent gas analysis. The sensitivity for acetylene reaches 0.00005%. But the IR method does not allow the detection of inert and diatomic gases, such as O₂ and N₂, whose molecules consist of identical atoms.

In addition, devices using these principles are laboratory-type instruments; their operation involves sampling and measurement preparation. They cannot be used for continuous measurements.

The most accurate continuous analysis devices use the following measurement methods:

- electrochemical [4], measurement error $\pm 1.5\%$;
- thermal conductivity [5], basic error $\pm 2\%$;
- photoionization [6], measurement error and reproducibility $\pm 10\%$;
- optical fluorescent [7], measurement error for SO₂ $\pm 20\%$;
- optical absorption [8], limits of permissible basic error $\pm 10\%$ (in the range from 50 to 100% LEL).

The most accurate is the BGA244 gas analyzer [9], which, like the one described in this article, uses the acoustic measurement principle. It does not use a reference gas, and measurements of thermodynamic properties of gas mixtures (sound velocity, temperature, and gas pressure) are conducted separately. The composition measurement error is less than 0.1%. Measurement speed is 4 samples/s.

3. CONCLUSION

A wide-range acoustic analyzer for binary gas mixtures has been developed and manufactured. It provides continuous measurement mode with a sensitivity of 0.025% and does not require periodic verification.

The prototype version of the device is used to measure the composition of air-freon 22 mixture in a physical experiment. In this version, the resonator with a temperature sensor is placed outside the device in the volume with the tested gas.

ACKNOWLEDGMENTS

The authors thank Yu.A. Khokhlov for useful discussions.

REFERENCES

1. *Alferov V.N., Vasiliev D.A.* Acoustic gas analyzer. // PTE. 2020. No. 5. P. 148.
2. *Menshikov V.G.* Patent SU No. 853520, 1981.
3. <https://www.rosteplo.ru/>
4. <https://granat-e.ru/>
5. <https://www.geo-ndt.ru/>
6. <http://www.metr-k.ru/>
7. <https://www.optec.ru/>
8. <http://www.gasdetecto.ru/>
9. <https://www.optec.ru/>

FIGURE CAPTIONS

Fig. 1. Block diagram of the acoustic analyzer: 1 – resonator housing, 2 – convection openings, 3 – electrodynamic emitter, 4 – electret microphone, 5 – openings for emitter and microphone, 6 – auto-generator, 7 – main and control temperature sensors, 8 – humidity sensor, 9 – controller.

Fig. 2. Resonance frequency of the resonator F_{res} and auto-generator frequency F_{AG} .

Fig. 3. Dependencies of resonance frequency on $\sqrt{M/\gamma}$ at different temperatures.

Fig. 4. External view of the gas analyzer.

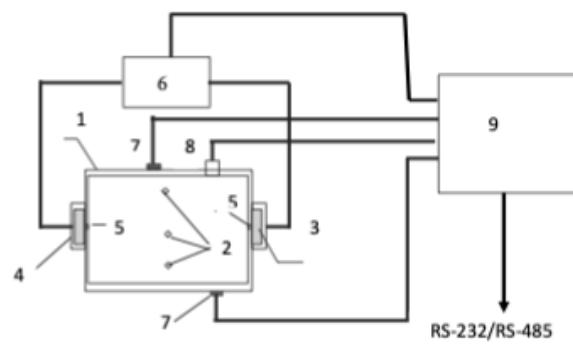


Fig.1

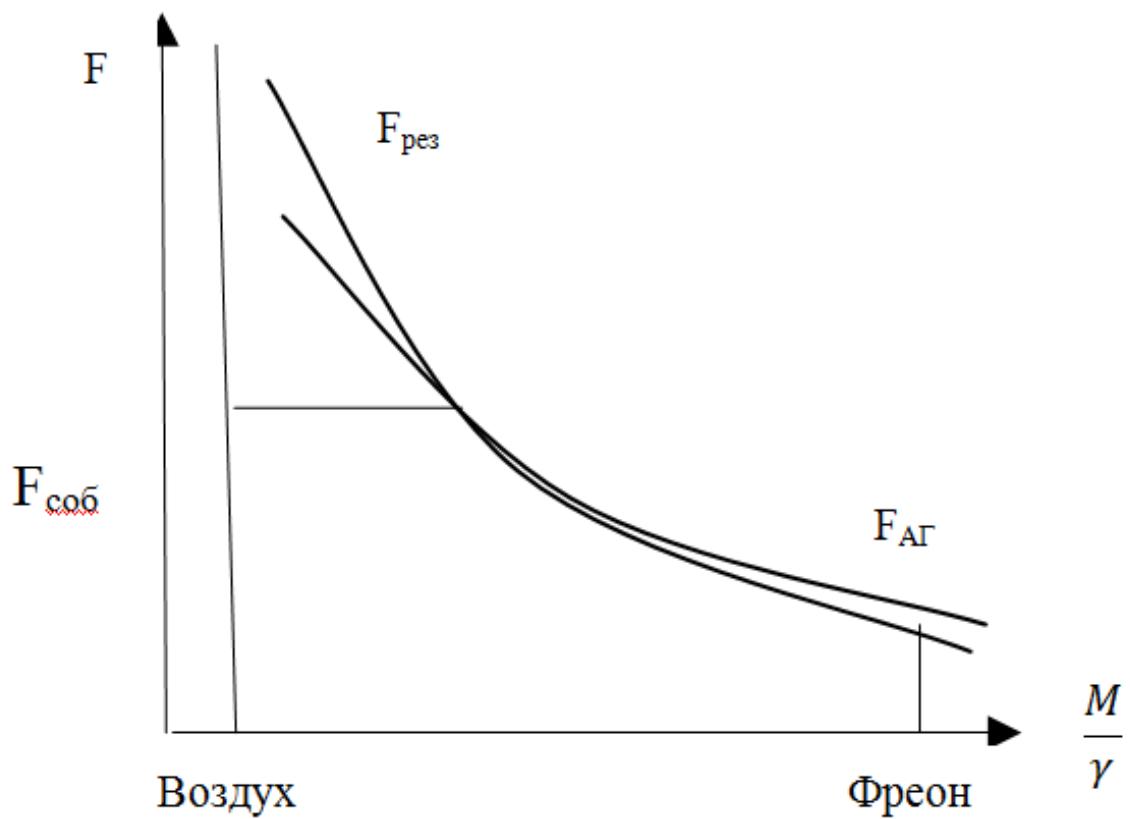


Fig. 2

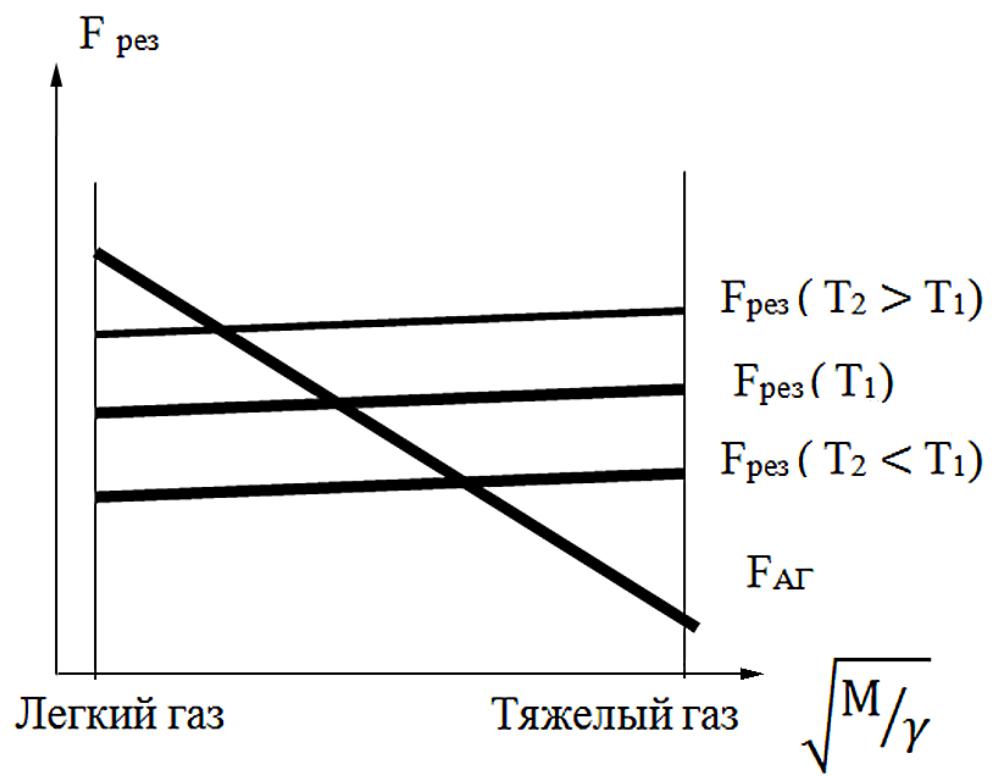


Fig. 3



Fig. 4.