Development of absolute acoustic gas thermometer for the state primary standard of the temperature unit – kelvin in the range 0.3-273.16 K in VNIIFTRI and the total standard uncertainty of the thermodynamic temperature measurements near the triple point of water

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Abstract. An absolute primary acoustic gas thermometer has been developed and successfully tested in VNIIFTRI. The acoustic gas thermometer is planned to be included in the Russian state primary standard of the temperature unit – kelvin in the range 0.3-273.16 K. The uncertainty of the thermodynamic temperature measurements with the acoustic gas thermometer near the triple point of water was experimentally researched.

1. Introduction

The new definition of the temperature unit kelvin requires new equipment for the Russian state primary standard of the temperature unit – kelvin in order to reproduce the temperature unit based on the thermodynamic laws. An acoustic gas thermometer is a promising tool for this purpose.

Primary acoustic gas thermometry exploits the relationship between the speed of sound, $u_0$, in an ideal gas in the limit of zero pressure and the thermodynamic temperature $T$ of the gas,

$$T = \frac{M}{\gamma N_A k_B} u_0^2$$

where $k_B$ is the Boltzmann constant, $M$ is the molar mass of the gas, $N_A$ is the Avogadro constant and $\gamma$ is the ratio of the heat capacity of the gas at constant pressure to its heat capacity at constant volume. For ideal monoatomic gases $\gamma = 5/3$. The speed of sound is determined from an acoustic resonance frequency $f$ and a radius $a$ in a spherical resonator when pressure $p$ tends to zero $u_0 = \lim_{p \to 0} u(p)$ [1-3].

The acoustic gas thermometer is shown in figure 1. The resonator is placed in a pressure vessel, filled with ultrapure helium. The temperature of the resonator is regulated by a heater, located on a heat exchanger. The pressure vessel is located inside a vacuum vessel. The vacuum vessel is placed in a liquid thermostat. The apparatus of the acoustic gas thermometer consists of a gas system, pressure measuring equipment, acoustic resonance measuring equipment, electromagnetic resonance measuring equipment and a temperature stabilization system. The copper resonator was obtained from LNE-CNAM (France). In 2017 the universal gas constant $R$ and the Boltzmann constant $k_B$ were
determined on the equipment of the acoustic gas thermometer, which was described in details in papers [1,2].

![Acoustic gas thermometer](image)

**Figure 1.** Acoustic gas thermometer

### 2. Resonator temperature stabilization system

The resonator temperature must be stable near the temperature of the triple point of water (TPW) 273.16 K during the time interval, needed for measuring acoustic resonance. To stabilize the resonator temperature a capsule type platinum resistance thermometer and a temperature meter MIT 8.20 were used. The thermometer was located in a heat exchanger. The heat exchanger was thermally connected with the resonator and its temperature was regulated by a heater. To measure a temperature gradient of the gas inside the resonator iron-rhodium resistance thermometers were located in the top and bottom hemispheres of the resonator. Before placing in the resonator the thermometers were calibrated in a TPW cell according to ITS-90. During calibration the resistance thermometers were measured by the bridge F18 with two values of the measuring current for extrapolation to a zero current. The measurement uncertainty of the resistance bridge F18 was 0.08 mK in temperature equivalent.

The temperature gradient was measured after temperature stabilization by subtracting the readings of the thermometers. The maximum difference between temperatures measured by the thermometers located in the top and bottom hemispheres of the resonator was 0.16 mK. Due to the specification the temperature measurement error of the temperature meter MIT 8.20 is 0.17 mK. The temperature drift during acoustic resonance measurements introduces the uncertainty of 0.37 ppm. Taking into account the temperature gradient the total relative standard uncertainty of temperature stabilizing is 0.70 ppm.

### 3. Admixture effect on molar mass

We used ultrapure helium 7.0N grade. Evaluation of the effects of impurities taken from the manufacturer's certificate of helium gives the relative standard uncertainty of the molar mass $M$ better than 0.5 ppm. Helium can be contaminated by desorption of impurities from pipeline walls and elements of the gas system during transportation of the gas from the pressure vessel to the resonator. Therefore a cryogenic trap, immersed in a Dewar vessel with liquid helium is used in the gas system. When passing ultrapure helium through the cryogenic trap the residual impurity content is determined by a saturated vapor pressure of corresponding impurities at the temperature of 4.2 K. The molar mass uncertainty after purification in the cryogenic trap is reduced to 0.1 ppm. All the impurities are frozen out effectively in the cryogenic trap except $^3$He. The contents of $^3$He in the ultrapure helium 7.0N grade is not standardized. The $^3$He contents in the Earth’s atmosphere is 0.137 ppm, that contributes to the uncertainty measurements of the same order. The analysis of desorption in the gas system, pumped
out previously up to 1 Pa and filled with pure helium with the pressure up to 300 kPa allowed to estimate the maximum desorption value of molecules from the inner surfaces of the system, because the contribution of desorption is inversely proportional to the helium pressure in the resonator, and the measurements were carried out starting with the pressure of 100 kPa. The contribution of the desorption to the uncertainty budget, measured by the resonance frequency shift, was 0.25 ppm per 2 hours. The gas-washing procedures were taking place before each measurement cycle to ensure a minimum level of impurities in helium. The standard uncertainty of the helium molar mass measurement was 0.30 ppm.

4. Measurement of the resonator radius

The resonator radius was determined by measuring electromagnetic resonance in the resonator, pumped out till the level of 1 Pa. The electromagnetic resonance frequency was measured using a vector network analyzer E5071C-4K5. The analyzer was synchronized by a rubidium frequency standard FS725. The radius of the resonator $a$ and eccentricities $\varepsilon_1$, $\varepsilon_2$ were calculated from the experimental frequency dependences of the electromagnetic resonance in the vacuum and are equal to $a = 49.9592973$, $\varepsilon_1 = 1.150 \times 10^{-05}$, $\varepsilon_2 = 5.65 \times 10^{-06}$. Total standard uncertainty for $a^2$ is 0.82 ppm.

5. Acoustic resonance frequency measurements

The system of acoustic resonance frequency measurements consists of condenser microphones mounted in the resonator, a signal generator of sound frequency AKIP 3418/1 and a lock-in amplifier SR830. The AC current is energized from a generator to a microphone-emitter, inducing acoustic oscillations. A preamplifier located in the vacuum vessel amplifies signal from a microphone receiver and it is applied to the lock-in amplifier synchronized by the frequency signal generator. The frequency signal generator is synchronized by the rubidium frequency standard FS725. The generator and the lock-in amplifier are controlled by a PC program and provide measurements of the frequency dependence of an acoustic signal. Measurements of frequency dependences of the acoustic signal were carried out at the pressure of the helium in the resonator in the range of 100-550 kPa with the interval of 25 kPa for modes (0,2)-(0,6). For each fixed pressure the frequency dependence of the squared sound velocity in the range $f_0 \pm 3g$ was measured in 50 points ($f_0$ – resonance frequency for mode $(0,n)$, $g$ – half-width of a resonance curve). Measurements were performed during increasing and decreasing frequency with the averaging. For the modes (0,2) and (0,3) the excess of the half-width measured is larger than for the modes (0,4)-(0,6). This is due to the fact that the resonance frequencies for the mode (0,2) and for the mode (0,3) are close to the resonance frequency of the resonator shell. Figure 2 shows the relative deviations of the measured squared sound velocity $u_{exp}^2$ from the approximation function $u_{ap}^2 = u_s^2 - A_{-1} (p)^{-1} = A_0 + A_1 p + A_2 p^2$ for the modes (0,4)-(0,6), where $A_{-1}$, $A_0$, $A_1$, $A_2$ – coefficients, vertical lines show the standard deviation. The total standard uncertainty of the acoustic measurements is 0.77 ppm.

![Figure 2](image.png)

**Figure 2.** Relative deviations of the measured squared sound velocity from approximation as function of pressure for the modes (0,4) – (0,6)
6. Total standard uncertainty of thermodynamic temperature measurements

The total standard uncertainty is calculated as the root square of the sum of the squares of the uncertainty budget elements. The uncertainty of the Boltzmann constant $k_B$ was not considered because it is known now with high precision [3] and will be fixed numeric values for the kelvin redefinition with no uncertainty and with 7 significant figures $k_B = 1.380649 \times 10^{-23}$ J K$^{-1}$ [4]. In accordance with recommendation [4], the Avogadro constant equals $6.02214076 \times 10^{23}$ mol$^{-1}$ with the standard relative uncertainty $1.0 \times 10^{-8}$. This uncertainty can be neglected. The uncertainty of the thermodynamic temperature measurements of the developed acoustic gas thermometer near the triple point of water is achieved 1.42 ppm.

| Sources and uncertainty components | The standard uncertainty (ppm) |
|-----------------------------------|-------------------------------|
| Temperature stabilization system  | 0.70                          |
| Molar mass $M$                    | 0.30                          |
| Radius of the resonator $a^2$     | 0.82                          |
| Acoustic measurements             | 0.77                          |
| Total standard uncertainty        | 1.42                          |

7. Conclusions

The total standard relative uncertainty of the thermodynamic temperature measurements near the triple point of water equals to 1.42 ppm. This means that the acoustic gas thermometer in the state standard reproduces absolute thermodynamic temperature with an uncertainty less than 0.39 mK in temperature equivalent and absolute temperature is traceable to the meter, the kilogram and the second. The results are in accordance with the proposals for absolute primary thermometry [5] and will allow us to implement the new definition of the kelvin [6].

References

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