Critical nozzles are widely used as standard means of measuring gas flow rate. The shape has a marked effect on the flow coefficient, and at present there are no standards for the use of critical nozzles, which means that individual calibration is required. Such standards also cannot be devised without experimental research. This has made it necessary to develop systems for calibrating such nozzles and performing metrological research.

Existing equipments can be divided basically into two types: In the first, the amount of gas passing through the nozzle is measured by a gravimetric method, while in the second it is measured from the pressure change in a constant known volume. Sometimes other methods are used, but they are not widely employed [1].

The present calibration system was developed at the Kazan' branch of the All-Union Technical Physics and Electronics Research Institute and belongs to the second type. The constant-volume method is preferable in the measurement of low flow rates for a gas with known thermodynamic parameters. Simple design and convenient operation are combined in this case with fairly high accuracy, which is comparable with that in the gravimetric method, or may even exceed it if light gases are used (hydrogen, helium), because a vessel of small volume is required for low flow rates, which can readily be made quite rigid, and therefore the capacity can be determined accurately. Also, the temperature difference is small in a small volume of gas, which also influences the accuracy favorably.

The system is intended for use in calibration and in researching the effects of various factors on the flow coefficients for constriction devices.

Existing equipments for similar purposes [2-4] have the major disadvantage that the gas flow is periodically interrupted, which causes transient processes and reduces the accuracy.

Figure 1 shows the simplified scheme, in which the gas from the pressure source is cleaned by the filter 1, while the micronozzle 7 is set up in the measurement section; the reduction valve 2 and thermostat 3 maintain present pressure and temperature at the inlet. The gas parameters are checked by the standard gauge 5, thermometer 6, and vibrational-frequency density meter 4.

The four calibrated vessels 15, 16, 17, and 18 have volumes correspondingly of 2.194, 9.673, 46.61, and 491.8 liter and are used to extend the measurement range. The vacuum pump 12 evacuates the vessels. The vacuum is monitored by the standard gauge 10 and the mercury manometer 14.

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The three-way stopcock 13 switches the gas flow direction. In the initial position, the flow is directed to the atmosphere, while when the valve is switched on, the flow is directed to the vessels. The opening time for the valve is controlled by an electronic timer with microswitch.

The system is operated in the following sequence. In accordance with the nominal flow rate, one of the four vessels is connected. This is evacuated by the pump 12 to a residual pressure of about 100 Pa (1 mm Hg), and then the pump 12 is switched off and disconnected from the collector by the valve 11. When the temperature has stabilized, the residual pressure and temperature in the vessel are measured.

The reduction valve 2 sets up the necessary pressure at the inlet to the nozzle 7. Valve 8 sets the flow rate through the nozzle. The gas flow through the normally open channel of valve 13 is directed to the atmosphere. When the pressure and temperature have stabilized (steady-state flow), readings are taken of the gas parameters before the nozzle and of the gauge 9. Stopcock 13 then switches the gas flow to filling the vessel, where the timer is automatically started as it is interlocked with the valve. The filling is followed from the gauge 9; when the pressure has risen to the initial specified value, the valve is closed. The filling ceases and the timer is halted.

It is necessary to switch the valve on and off at the same gauge reading in order that the amount of gas in the intermediate volume, from the nozzle to the valve, is the same before and after filling the vessel.

A certain time is allowed to elapse for the temperature in the vessel to equalize, after which the pressure and temperature are recorded.

The known parameters in the vessel before and after filling are used with the volumes of the vessel and collector as well as the filling time to determine the mass flow rate through the nozzle:

$$m_m = \frac{P_2 - P_1}{T_2 - T_1} \frac{V}{RZ_2},$$

where $P_2$ and $T_2$ are the gas pressure and temperature in the vessel after filling, $P_1$ and $T_1$ are the same before filling, $V$ is the volume, $R$ is the gas constant, $Z_2$ is the compressibility coefficient at $P_2$ and $T_2$, and $t$ is the filling time.

The theoretical value of the mass flow rate for critical flow is given by [5]

$$m_t = F P_0 \sqrt{k \left( \frac{2}{k+1} \right) \frac{(k+1)/(k-1)}{ZRT_0}},$$

where $F$ is the area of the critical section, $P_0$ and $T_0$ are the absolute pressure and temperature ahead of the nozzle, $k$ is the adiabatic parameter, and $Z$ is the compressibility coefficient at $P_0$ and $T_0$.

The flow coefficient $\mu$ is found as the ratio of the measured flow rate to the theoretical rate, i.e.,

$$\mu = \frac{m_m}{m_t},$$

where $m_m$ is defined by (1) and $m_t$ by (2).

In general, the flow coefficient is dependent on the profile and surface finish of the nozzle, as well as on the composition and Reynolds number $Re$ for the gas. In calibration, one determines $\mu$ for a given nozzle as a function of $Re$. In research, one estimates the effects on $\mu$ from the other factors.

The error $\delta_\mu$ in the flow coefficient can be put as follows from (3) on the basis of (1) and (2) if the components have identical distributions:

$$\delta_\mu^2 = \delta_\Delta P^2 + \delta_P^2 + \delta_\gamma^2 + \delta_T^2 + \delta_{p_0}^2 + \frac{1}{4} \delta_F^2,$$

where the relative errors in the measured quantities (indicated in the subscripts, where $\Delta P = P_2 - P_1$ and $T$ is the temperature in the vessel) are as follows in percent: $\delta_{\Delta P} = 0.15$, $\delta_P = 0.1$, $\delta_T = 0.07$, $\delta_{p_0} = 0.05$, $\delta_{T_0} = 0.2$, $\delta_F = 0.17$.

The errors in $R$, $Z$, and $k$ are negligible.

With these data, $\delta_\mu < 0.30\%$.