A VERSATILE HIGH-PRECISION AUTOMATIC TEMPERATURE REGULATOR ASSEMBLED FROM STANDARD COMPONENTS

V. V. Aleksandrov, A. N. Borzyak,
G. A. Kuvshinov, and I. I. Novikov

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An automatic temperature regulator assembled from existing components and having broad applications is described. The error limits of temperature regulation in the static and dynamic regimes do not exceed 10^{-4}°K.

In the investigation of the temperature dependence of physicochemical, mechanical, and other properties of substances it is required to maintain the object of investigation or elements of it at a constant temperature throughout the testing period or to create conditions such that the ambient temperature is kept equal to the temperature of the object with a high degree of precision. Manual temperature regulation is complex and does not always ensure high measurement accuracy, and so it is scarcely ever used at the present time, having been superseded by the automatic temperature regulator (ATR).

A large number of ATRs are described in [1-7], many of which are designed for the solution of a rather restricted experimental problem or are assembled from a minimal number of commercially manufactured units, thereby discouraging their general application in measurement practice. A comprehensive analysis [8] of the design and operating principles of automatic regulators has shown that the "building-block" principle of ATR design, based on the utilization of commercially available components, permits the synthesis of universal, operationally reliable, high-precision ATRs for the investigation of a broad range of material properties.

Industry manufactures the VRT-2 automatic temperature regulator, which has temperature-regulation error limits of ±0.5°K in the interval from 273 to 1873°K. Its essential shortcomings are low precision of temperature regulation, particularly in connection with thermophysical investigations, and limited application in connection with low-temperature investigations.

Using a preamplifier for the input signal and a wide-range controllable output power amplifier, we have developed a versatile multipurpose ATR, which is based on the VRT-2 regulator and is assembled from existing components. A block diagram of the regulator with schematically represented calorimeter and adiabatic shield is given in Fig. 1. A note on the regulator has been published earlier [9]; at the time of publication we had already incorporated significant changes in the design of the ATR and VRT-2 units.

The system operates as follows. The output signal from the temperature-difference sensor 3, which in this case is a differential thermocouple with Cu + 0.3% Fe alloy and Chromel electrodes inserted between the calorimeter 1 and shield 2, is sent through the master section 5 to the input of the type F116/1 photocompensated amplifier 8. Then it is additionally amplified by the self-excited amplifier 11 of an I-102 unit and is sent to the input of the analog controller 13 of an R-111 unit, in which a control-function signal is generated to regulate the operation of the photocompensated amplifier 14 of a U-1136 dc voltage stabilizer. Power is delivered from the output of the U-1136 to the shield heating element 4. The current output of the F116/1 amplifier is matched with the input of the self-excited amplifier and recording unit 12 by insertion of the divider 10 after the F116/1 output.

We consider the operation of the regulator in the example of a calorimetric experiment. After cooling of the calorimeter and adiabatic shield to the minimum temperature, at which the measurements are begun, the regulator is adjusted. Since the thermocouple Cu + 0.3% Fe electrodes, which run from the cold zone to a room-temperature zone and are connected to the

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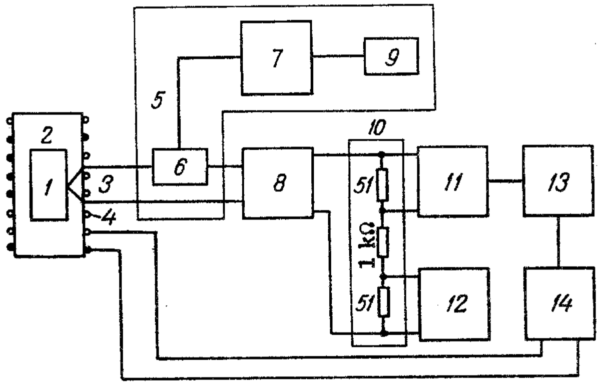

Fig. 1. Block diagram of automatic temperature regulator for the temperature interval 2-360°K.

input of the F116/1 photocompensated amplifier, can acquire a thermo-emf due to the inhomogeneity of the electrodes, it is compensated by the emf of the master section, which consists of the stepped divider 6 and the calibrated divider 7 of the I-102 unit. The stepped divider permits 10- and 100-fold attenuation of the signal from the calibrated divider, thus promoting more precise compensation of the thermo-emf, during which the input of the amplifier 11 of the I-102 unit is shorted. With this master-section configuration, however, heavy demands are imposed on the temporal stability of its signal and the noise level. The noise of the I-102 unit master section is associated with noise in the stabilized voltage source, which is supplied by the ac line. The stabilization factor of the given voltage source is approximately 1000. The time drift of the compensation emf is determined by the on and off times of the I-102 unit thermostat. These times are roughly 15 and 75 sec, respectively. Whereas the noise and temporal instability of the master-section signal do not affect the temperature regulation precision at temperatures above 4 or 5°K, below 4°K they exert an appreciable influence on it. Consequently, the stabilized voltage source was removed and replaced by the Baken battery 9. In this case, the drift of the compensation emf does not exceed 10^{-8} V/h, and the noise level is determined by the internal noise of the F116/1, in which the differential thermocouple signal is preamplified. All of this makes it possible to realize compensation of the electrode thermo-emf only prior to the beginning of each series of measurements.

The preamplified signal is sent through the matching divider to the input of the self-excited amplifier of the I-102 unit for additional amplification. It is evident from the block diagram that compensation of the emf of the hot (cold for the VRT-2) junctions is unnecessary, because only the signal generated in the differential thermocouple due to the action of the difference ΔT is important. The signal amplified by the self-excited amplifier is sent to the R-111 analog controller, which can execute a proportional, proportional-plus-integral, or proportional-plus-integral-plus-derivative (PID) control function.

It has been noted [8] that the most favorable regulation conditions in adiabatic calorimetry are realized with the generation of a PID temperature control function. Its hybrid control function in the final-control amplifier is given by the equation

$$E = -\mathrm{P}\,T - \mathrm{I}\int T d\tau - \mathrm{D}\,(dT/d\tau), \tag{1}$$

in which τ is the time, P, I, and D are coefficients depending on the parameters K_p, T_i, and T_i/T_d set in the R-111 unit, and T is the absolute temperature. The signal E is sent to the terminals for connection of the reference-voltage battery to the photocompensated amplifier of the U-1136 dc voltage stabilizer, but the battery itself is removed, and the U-1136 stabilizer functions as a controllable power amplifier.

The values of the coefficients P, I, and D are chosen in a preliminary series of experiments and are determined by the heat transfer between the calorimeter and the surrounding medium and by the heat capacity of the calorimeter. In the interval from 2 to 360°K the heat capacity of metals and alloys varies roughly by three or four orders of magnitude, requiring variations of the coefficients I and D over a broader range than can be accomplished with the actual parameters T_i and T_d of the R-111 unit. Accordingly, the R-111 is equipped with a switch, which changes the capacitance in the integrating and differentiating circuits,

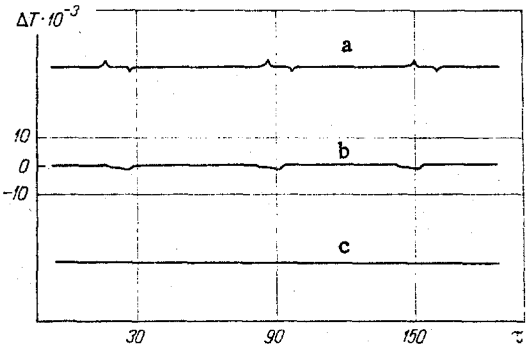

Fig. 2. Temperature-regulation traces in the initial period of a calorimetric experiment. a, b) With the thermostat of the I-102 unit in operation; c) with the thermostat off.

making it possible to shorten the integration and differentiation times by 1/1.3 and 1/10, respectively, relative to the previous times for the R-111 unit, and to make a finer selection of T_i and T_d in the course of the experiment. Thus, once the PID control mode has been set in the R-111 unit by specification of the values of the parameters K_p, T_i, and T_d and the maximum required power level has been set in the U-1136 stabilizer, the ATR adjustment procedure is terminated and the instrument is ready for operation.

When the heating element of the calorimeter is turned on, the temperature of the calorimeter begins to rise, the thermocouple acquires an emf, and simultaneously with the occurrence of ΔT power is supplied to the shield heating element. Due to the thermal lag of the shield, for a certain time after the calorimeter heating element is turned on the temperature of the shield will be lower than the temperature of the calorimeter. When the heating element is turned off, the situation changes. The thermal lag of the shield is determined by the design and technological characteristics of its fabrication and will not be discussed here. Recording of the increment ΔT and selection of the parameters of the R-111 unit are realized by means of the KSP-4 self-writing potentiometer 12, which makes it possible to exhibit the influence of activations and deactivations of the thermostat on the self-excited amplifier of the I-102 unit, and the thermostat is disconnected from the I-102 unit supplying its IP-3 source. Figures 2a-c give three typical temperature-regulation traces in the initial period of a calorimetric experiment with the thermostat operating and turned off. Figures 2a and b refer to an experiment with the thermostat off and respective gains of 22,000 and 11,000 for the F116/1 amplifier, and Fig. 2c represents the operation of the regulator with the thermostat off. It is evident from Figs. 2a and b that during the thermostat on-time, which is ≈15 sec, a temperature imbalance is observed between the calorimeter and the shield, inducing a systematic error in the heat-capacity measurements.

Figure 3 gives a trace of the temperature imbalance (deviation from the null line) obtained in the course of a calorimetric experiment at 100°K; this trace differs from the analogous trace published in [9]. As a result of the modifications incorporated into the ATR design and VRT-2 unit, it has been possible to reduce the transient periods and enhance the temperature-regulation precision. The maximum temperature imbalance does not exceed 0.002°K.

In the course of a series of heat-capacity measurements, particularly in the temperature interval 2-30-40°K, operator intervention in the operation of the ATR is necessary in order to increase the maximum power output level of the U-1136 (the power can be smoothly regulated from 0 to 20 W) and to switch the values of the parameters K_p, T_i, and T_d of the R-111 unit. Both of these operations are executed in the initial period of the calorimetric experiment and do not exert any appreciable influence on the measurement process.

Figure 4 gives the results of deviations of the measured values of the heat capacity of the empty calorimeter C_{exp} from the smoothed values of C. It is evident from the figure that the maximum random measurement error is not greater than 0.5% in the interval up to 20°K and 0.2% at higher temperatures.

Above, we have described the operation of the regulator for adiabatic calorimetry applications. It has been used in a similar fashion for measuring the thermal conductivity of certain alloys. Replacing the differential thermocouple with a single-junction thermocouple

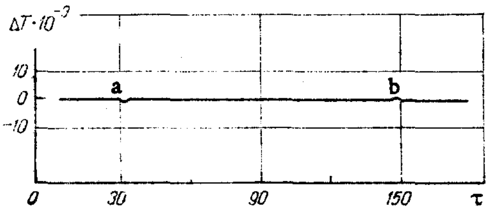

Fig. 3

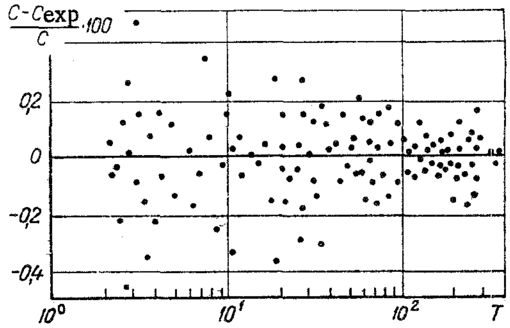

Fig. 4.

Fig. 3. Diagram of temperature imbalance $\Delta T \cdot 10^{-3}$ (°K) versus time τ (sec) in calorimetric experiment; a) calorimeter heater turned on; b) heater off.

Fig. 4. Relative deviation of experimental heat-capacity data from smoothed values $[(C - C_{exp})/C] \cdot 100\%$ vs T, °K.

or resistance thermometer and setting the necessary compensation emf in the master section, we use the regulator in our laboratory to maintain a constant temperature in measurements of the electrophysical and acoustical properties of metals and alloys.

The developed temperature regulator configuration is distinguished by high operational reliability, relatively low cost, and assembly from mass-produced commercial instruments. The modifications introduced in the VRT-2 units are easily realized and can be recommended for the industrial manufacture of low-cost high-precision regulators with a broad range of applications at low temperatures.

NOTATION

T, temperature imbalance; K_p, proportional-control gain; T_i, integration time; T_d, differentiation time; E, control function signal.

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