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Features of Computer Control Systems Designing for Precision Thermoelectric Coolers

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The effective electrical scheme, the operating algorithm, as well as the working sample of a thermoelectric precision thermostat have been developed offering the possibility of autonomous operation, continuous monitoring, and recording of the temperature using a computer or smartphone. It is shown that the developed algorithm provides effective shockless control and accuracy of maintaining the temperature of 0.03 °C, with a power consumption of 3-7 W. A design and a specialized numerical control system for a multistage cryogenic thermoelectric cooler have been developed.

Keywords: thermoelectric thermostat, temperature regulator, computer system.

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Introduction

Thermoelectric heat pumps have several important advantages for producing compact thermostats based on them, i.e. miniature refrigerators with high autonomy time for biomedical applications, radiators in the form of a completely black body model for calibration of thermal imagers, and pyrometers [1,2].

A separate important aspect is the development of cryogenic thermoelectric coolers operating at temperatures below 100 K, associated with the needs of the aerospace industry in satellite cooling systems, especially in sensors of radiation and infrared radiation [3-7]. Thermoelectric coolers for highly efficient vacuum cooling to a level below 150 K are of particular interest. Six-stage thermoelectric modules using classical thermoelectric materials based on solid solutions $(Bi, Sb)_2(Te, Se)_3$, when choosing the optimal compositions provide the maximum difference temperatures 135 - 145 K [8]. Integrated sensors of cryogenic temperatures are described in [9, 10]. The properties of thermoelectric materials based on PbTe were investigated in [11-13], where their sufficient efficiency was shown.

Photodiodes based on InSb compounds are traditional semiconductor sensors in the middle infrared region and require cooling to a temperature of 77 K [14,15]. Lead telluride has a similar bandgap E_g = 210 meV at T = 77 K and can be also used for the manufacture of IR sensors [16, 17]. The advantage of PbTe over InSb is the temperature-increasing tendency of the bandgap. Thus, it is possible to use PbTe photodiodes up to a cooling temperature of 150 K [18], which made it possible to cool these sensors using a multi-stage thermoelectric module [19].

The main advantages of systems based on thermoelectric converters are their compact size, high reliability, and a long lifetime without service. It should also be noted the minimal inertia and the ability to switch very quickly between the mode of absorption and heat dissipation. This allows a design of precision thermal stabilization systems however requires the development of effective software and circuit solutions.

Traditionally, the main quality indicators of automatic control systems are formulated based on the requirements for the form of reaction of a closed system to a step change of the setpoint. However, this criterion is very limited, in particular, it does not say anything about the magnitude of the attenuation of measurement noise or the impact of external disturbances [18].

I. Features of development of a precision thermoelectric thermostat

Since in precision systems there is a need to maintain the temperature with an accuracy of 0.01 ºC, the most important factors are the form of response to external disturbances, in particular, over-regulation and the time of setting the set temperature; the form of response to measurement noise and their minimization; in the case of autonomous applications, energy savings in the mode of maintaining the set temperature. On the other hand, the use of thermoelectric converters imposes a number of limitations, in particular the limited dynamic range of changes in the system and the need for smooth switching of control modes. Actually, it is not recommended to directly use pulse-width modulation to control the power of the thermocouple, as shock loads significantly reduce their service lifetime. Discrete implementation of the controller to ensure the desired accuracy requires the use of ADCs with high resolution. Since the efficiency of thermocouple depends not only on the supplied power but also on the temperature of the opposite junction and the efficiency of heat removal from it. At a certain power supply, the thermocouple can provide a certain maximum temperature difference between the cold and hot side, and there may be a situation where the increase in thermocouple power does not reduce the cold side temperature due to a rapid increase in hot side temperature due to limited heat dissipation in specific conditions. Therefore, it is necessary to provide additional feedback and algorithm for correcting the operation of the system taking into account the temperature of the opposite junction of the thermocouple, as well as the power reserve of the cooling system and effective control algorithms.

An important advantage of thermal systems based on thermoelectric converters is the absence of zero cooling capacity (heating), ie if the PID controller requires a negative effect on the object, the controller changes the polarity of the thermocouple and heat is pumped in the opposite direction. The implementation of such an algorithm significantly increases the accuracy and speed of regulation.

In steady-state operation and with small perturbations, in particular it is necessary to ensure the absence of temperature jumps of the hot side of the thermocouple, the system with the PID controller is almost linear. But the process is non-linear, due to the power limit. The main manifestation of the restriction mode is the integrated saturation in the process of the system entering the mode, which leads to the delay of the transient process. The essence of this problem is that if the signal at the input has reached the limit, the signal at the output of the integrator continues to grow, but this signal is no longer involved in regulation due to the saturation effect. Compensation of the effect of integral saturation is possible through additional feedback for transmission of error signals at the input of the integrator or employing algorithmic prohibition of integration at saturation that was realized.

Taking into account these features, a block diagram of the control system of a precision thermoelectric thermostat has been developed (Fig. 1,2).

Since the digital controller processes discrete values, the accuracy of control is significantly affected by the resolution of temperature measurement. To ensure high accuracy as a temperature sensor used precision platinum thermistor PT100, which is included in the Wheatstone bridge circuit (Fig. 3). The other shoulders of the

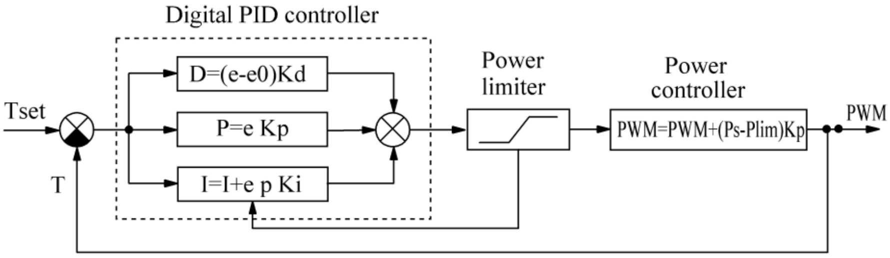


Fig. 1. Digital PID controller with compensation of the effect of integral saturation.

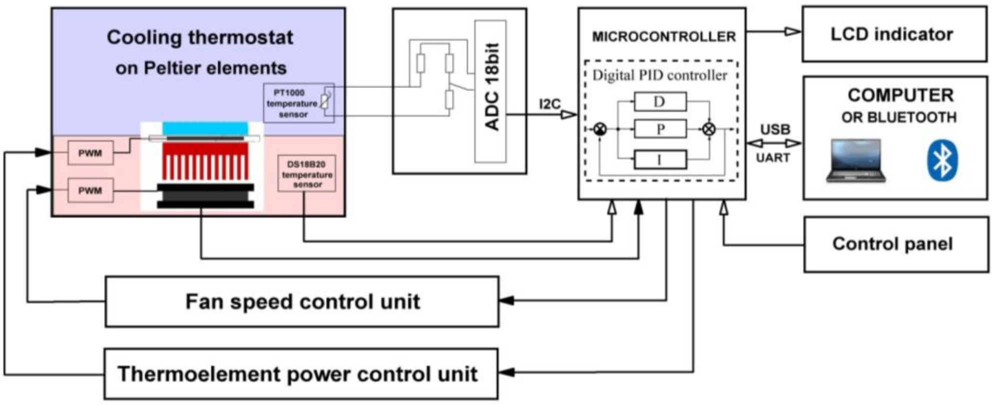


Fig. 2. Block diagram of a precision thermoelectric thermostat control system.

measuring bridge are built on high-precision thermostable resistors. The measuring bridge is powered by a precision reference voltage source. The bridge unbalance voltage is applied to the differential input 18 of the bit I2C ADC, with a built-in software-controlled input signal amplifier. With the right components, the discreteness of the temperature measurement will be at least 0.01 °C.

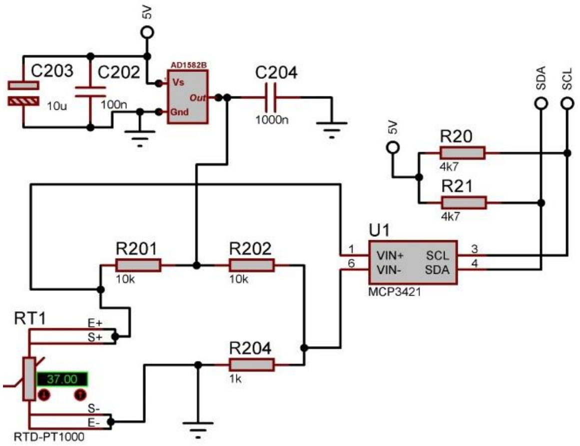
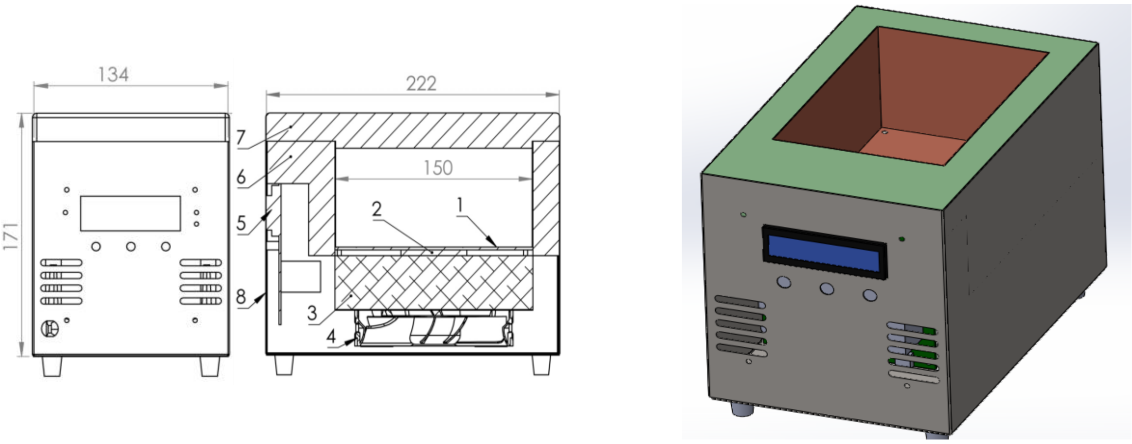


Fig. 3. Schematic diagram of temperature control.

The module of smooth control for powering the thermoelectric module is realized according to the scheme of DC-DC of the voltage converter. The microcontroller with the help of a pulse-width modulated signal through the transistor and the power choke can smoothly change the voltage on the thermocouple in the range from almost zero to the supply voltage. Using an internal ADC, the controller measures the voltage and current through the shunt, thus implementing power feedback. The switching of cooling-heating modes of the thermocouple is realized according to the classical scheme of the H-bridge on the optocoupled MOS FET assemblies TLP5752. This implementation firstly provides a wide range of input voltages and high efficiency of the converter, which allows in steady-state to apply a small power to the thermocouple (3-7 W) with minimal losses on the power elements of the circuit, and secondly provides a smooth (shockless) mode of the thermocouple for its maximum service lifetime.

These circuit and software solutions made it possible to design a small precision thermostat (Fig. 4), with a wide range of input voltages of 12-24 V for use both in stationary mode and in vehicles, as well as autonomous operation when powered by a portable Li-ion battery.

The advantages of this design are simplicity and high reliability, compactness, and portability, at a weight of 1-1.5 kg, the useful volume of the inner chamber is 1.125 liters. Accuracy of temperature maintenance ± 0.03 °C. Reaching the mode takes about 10 minutes and is shown



a) b)

Fig. 4. Design (a) and general view (b) of the thermoelectric thermostat. 1 – internal chamber (aluminum or copper); 2 – thermoelectric element, 3 – aluminum radiator, 4 – fan, 5 – controller board with display and controls, 6 – thermal insulation, 7 – cover (polystyrene foam), 8 – stainless steel housing.

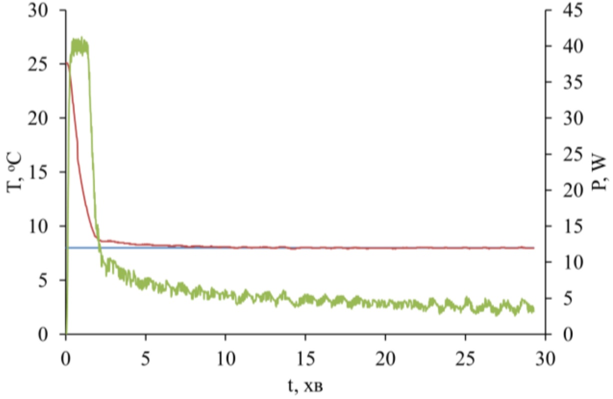


Fig. 5. Schedule of the thermoelectric thermostat reaching the mode. The set temperature is a blue curve, the temperature in the chamber is a red curve, the power of the thermocouple is a green curve.

in Fig. 5.

As can be seen from the graph in steady-state, the power consumed by the thermocouple is not more than 5 W at an ambient temperature of 25 °C. That, given the 1.5 watts consumed by the fan and electronics, gives a lithium battery life of about 7 hours with a capacity of 45 watts (weight 0.5 kg).

The main disadvantage of the thermostat on thermoelectric elements is the rapid increase in temperature in the chamber when the power supply is interrupted. This is due to the flow of heat that is stored in the radiator of the hot side (about 40 °C) through the thermocouples and is virtually independent of the thermal insulation of the housing. Given this autonomous power supply for such devices is in many cases mandatory.

II. Development of a multi-stage cryogenic thermoelectric cooler

The design of an infrared diode sensor based on indium doped PbTe with a multi-stage thermoelectric cryogenic thermoelectric cooler required to ensure the temperature of the sensor is considered in ref. [17]. Schematically, multi-stage cascade coolers are shown in Figure 6. It consists of four stages conventional thermoelectric cooler based on Bi_2Te_3, and provides a temperature of 200 K at a hot side temperature of 300 K [19].

A single-watt two-stage cryogenic module of special design with compensation of thermal deformations allows cooling the IR sensor to a temperature of 160 K. The cryogenic module consists of the first stage of 20x1.8 mm 4 pairs and the second stage of one pair of 6x1.8 mm. Further heat is removed by four stages of 12, 28, 64, 126 thermoelectric pairs. The total power emitted on the hot side does not exceed 100 watts, which is designed for air- or water-cooling radiator.

When designing control systems for multi-stage modules, the relationship between the stages should be taken into account, as the efficiency of the thermoelectric unicouples depends not only on the input power but also on the temperatures of the opposite junction and the efficiency of heat removal from it. Therefore, it is necessary to provide additional feedback and algorithm for correcting the operation of the control system taking into account the temperatures of the opposite side of the thermoelectric unicouple, an effective control algorithm, as well as the power reserve of cooling systems.

Considering these features, a structural diagram of the control system for a cryogenic thermoelectric cooler was developed to ensure the operation of the IR sensor (Fig. 7). Since the digital controller processes discrete values, the resolution of the temperature measurement significantly affects the control accuracy. To ensure high accuracy, a bridge circuit was used as a temperature sensor as in the case of the aforementioned thermostat (Fig. 3), but separate PT1000 temperature sensors were installed for both the cold side of the cryogenic module and the conventional one, respectively, the ADC was replaced with a four-channel MCP3424.

The module for smooth power control of four cascade thermoelectric coolers is implemented according to the DC-DC voltage converter circuit, similar to that for the thermostat. This implementation provides a smooth control mode with a wide range of input voltages and a high efficiency of the converter, allows a constant mode to supply a small power to the thermocouple with minimal losses on the power elements of the circuit, contributes to the maximum service lifetime.

Both standalone operation and the ability to connect to a computer for convenient configuration and monitoring of operation are provided.

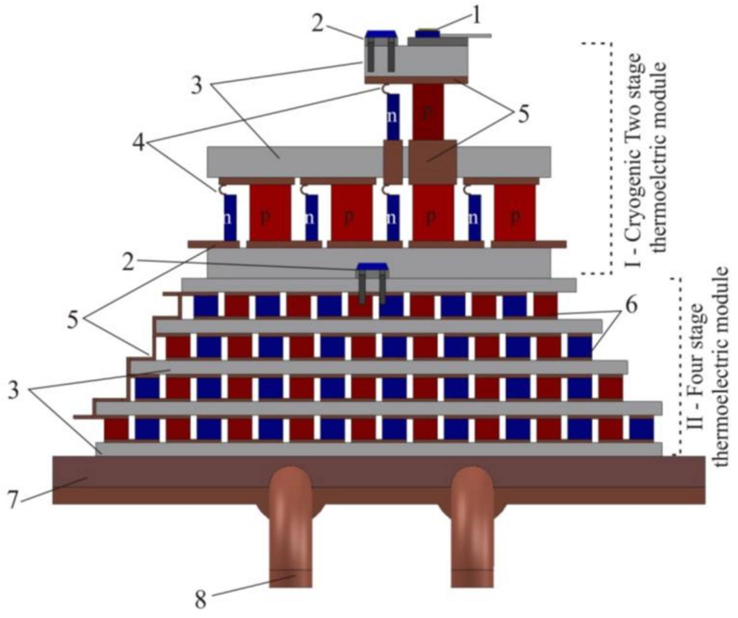


Fig. 6. Design of a multistage thermoelectric cryogenic cooler. 1 - cooled IR photodiode, 2 - platinum thermistors, 3 - BeO_2 ceramics, 4 - tape with copper foil, 5 - copper busbars, 6 - p-n legs of a multistage thermoelement, 7 - radiator, 8 - heat pipe [19].

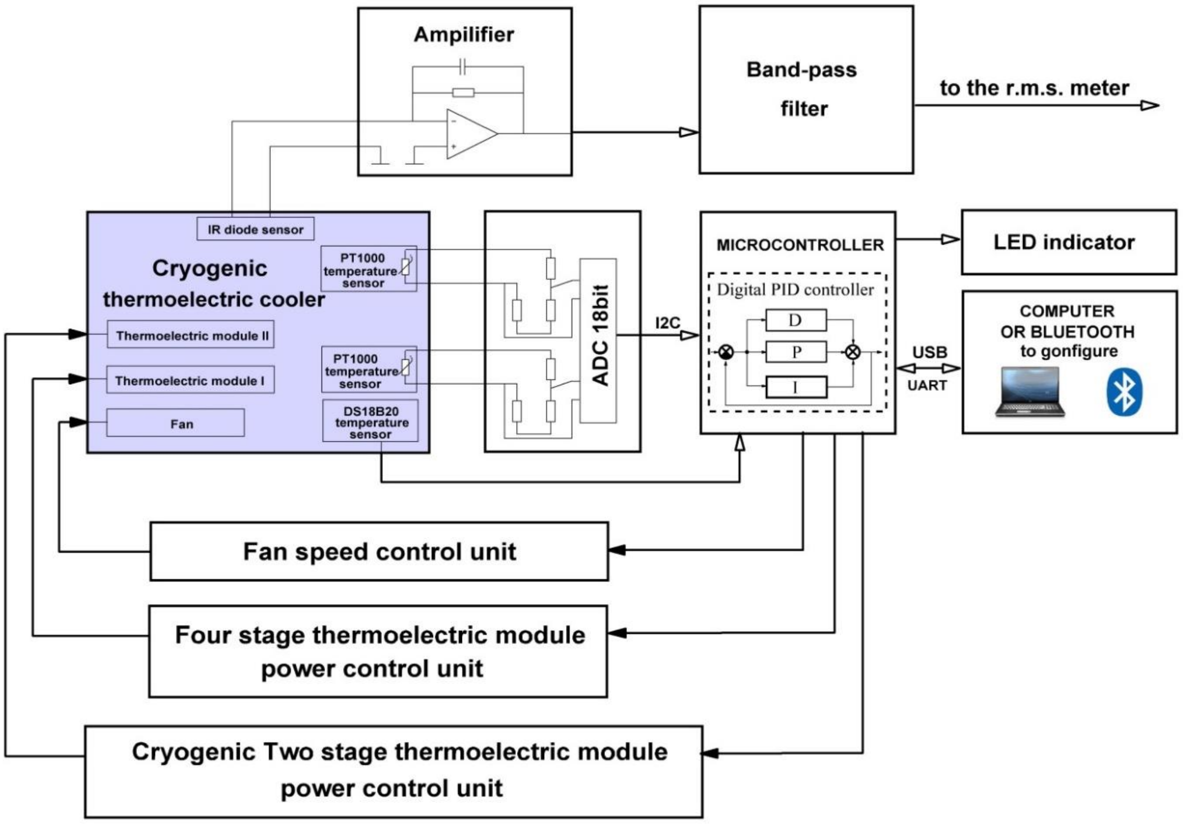


Fig. 7. Block diagram of a specialized computer control system for a thermoelectric cooler to ensure the operation of an IR sensor.

Conclusions

1. An effective electrical scheme and an operating algorithm have been developed. A working sample of a thermoelectric precision thermostat has been designed with the possibility of autonomous operation, continuous monitoring and recording of the temperature log using a computer or smartphone. It is shown that the developed algorithm provides effective shockless control and an accuracy of maintaining the temperature of 0.03 °C, with a power consumption of 3 - 7 W.

2. A specialized computer control system for a multistage cryogenic thermoelectric cooler have been developed.

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Особливості проектування комп'ютерних систем керування прецизійними термоелектричними охолоджувачами

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Розроблено ефективну електричну схему та алгоритм роботи, а також робочий зразок термоелектричного прецизійного термостата з можливістю автономної роботи, безперервного контролю та ведення журналу реєстрації температур за допомогою комп'ютера або смартфона. Показано, що розроблений алгоритм забезпечує ефективне безударне управління та точність підтримання температури 0,03 °С, з енергоспоживанням 3 - 7 Вт. Розроблена конструкція та спеціалізована комп'ютерна система управління багатокаскадним кріогенним термоелектричним охолоджувачем.

Ключові слова: термоелектричний термостат, регулятор температури, комп’ютерна система.