COMBINATION OF POWER CONVERTERS AS A METHOD FOR SOLVING THE PROBLEMS OF MODERN INSTRUMENT MAKING

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• *Positive experience of assuring the required thermal conditions for commonly used instruments in real operating conditions of special, medical and energy purpose products acquired due to the use of combined cooling and thermostatting devices with embedded thermoelectric converters confirms a good outlook for their application. Low values of thermodynamic perfection degree of devices based on thermoelectric effects are very well compensated by their high operational characteristics, the possibility of their introduction into various instrumental solutions and circuitry. The immediate tasks of the enterprise foresee the use of thermoelectric converters for thermal stabilization of microbolometer matrices, as well as employment of reference IR radiation sources for IR imaging devices in the enterprise developments. The efficiency of their introduction into created products is largely determined by the degree of developers' skill, the working knowledge of modern achievements in engineering and technologies. The use of thermoelectric converter as a part of developed product supposes the use of standard electric power supply sources or creation of special electric converters for specific unique thermoelectric modules. We think it necessary to support the decision of NASU leaders on the revival and expansion of holding scientific and technical branch meetings of specialists in heat engineering.*

Introduction

The purpose of this work is to show the necessity and good prospects for creation of combined medium-temperature and cryogenic coolers comprising thermoelectric power converters as exemplified by "Arsenal" developments in the infra-red (IR) projects, medical and power engineering.

The main direction of works of scientific-production complex №3 (structural division of "Arsenal" State Enterprise for Special Device Production") is creation of IR technology products based on the use of special IR radiation detectors remotely recording thermal radiation of objects under observation, contrast in given spectral range.

Modern radiation detectors perform most efficiently only with the medium-temperature or cryogenic level of cooling the detectors' sensitive elements [1]. As strongly indicated by many years' expertise of the enterprise, the outlook for IR device being developed is largely determined by the success of solving technico-economic problems of creation and use of special systems for cooling its radiation detector and thermal protection of assemblies critical to thermal conditions.

Specialists of scientific-production complex №3 have acquired engineering solutions for creation of cooling and thermostatting devices for a number of IR devices intended for application in steady-state, transportation and mobile conditions, as well as for devices used in medicine and gas industry. In so doing, design of cooling and thermostatting devices for mobile IR-products is the most complicated integrated problem: one should implement the thermophysical operating conditions of a radiation detector, the product component part, used in the intensive long-term high altitude and speed conditions of interaction with the velocity head of ram air.

Note: Cooling devices of medium-temperature and cryogenic levels for medicine and gas industry were developed independently.

Analysis of operating conditions, as well as requirements to energy characteristics of created IR products, to instruments (devices) of medicine and gas industry shows the necessity to involve the accomplishments of a wide spectrum of power converters, their combination in the most rational layouts.

Thus, for aerospace products and power converters of gas industry characterized by problems of heat exchange with ram air and possibility of "actuation" of the energy of high-pressure gas flow, respectively, it is reasonable and necessary to use a combination of the Ranque-Hilsch and Peltier- Seebeck effects.

To improve the operating characteristics of IR observation systems, as well as bottled throttling systems of IR engineering, there is a good outlook for using thermoelectric power converters with a simultaneous solution of heat removal and thermal protection problems.

2. Basic engineering solutions for creation of special coolers implemented by the enterprise specialists

2.1. Independent thermal protection of radiation detector's sensitive element

In the period from 1973 to 1975 the aircraft-based IR engineering product was cardinally retrofitted with the aim of increasing its sensitivity and thermal stability under short-term conditions of intensive kinetic heating. The retrofit was implemented by using a radiation detector supplemented with a single-stage thermo-electric cooler (TEC) and substitution of *PbS*-based sensitive element by *PbSe* material. The cooler introduced into device package ∩8 × 12 mm and consuming the electrical power of $P \leq 0.6$ W with the operating current value up to 0.4 A reduced the temperature of sensitive element by 35 – 45 K. Introduction of a TEC into the bulk of a radiation detector installed in the unit swinging in the solid angle (Fig. 1) and characterized by extremely restricted heat removal conditions (Fig. 2), called for a solution of a series of technological and design problems of thermoelectric instrument making. As a result, a basically new engineering solution appeared [2]. The retrofit assured the required values of product sensitivity and thermal stability both in air standing patrol mode and at short-term peak temperature values of ram air coming to the product. One of the first low-current commercially producible TEC designs was developed on a tight schedule by specialists of Special Design Technological Office "Phonon" (Chernivtsi) and Odessa Technological Institute of Refrigeration Industry (Odessa). IR-device FRO-ES-131 was commercially produced by "Kwartz" plant (Chernivtsi) and successfully applied in the USSR up to the 90-s.

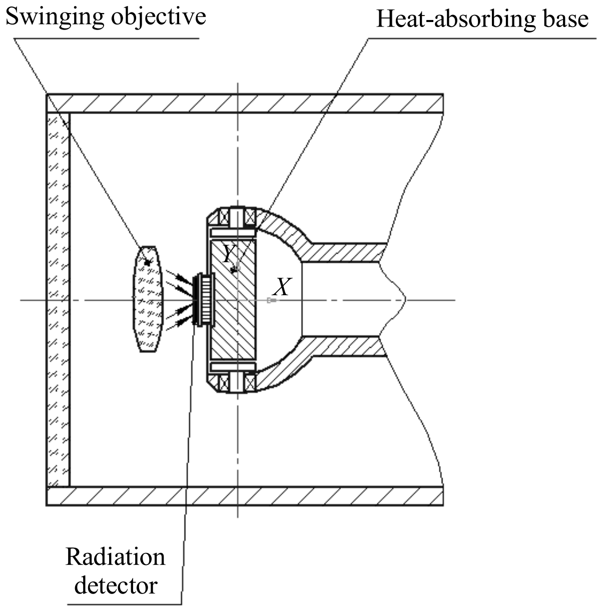

Fig. 1. Basic diagram of thermal stabilization of IR imaging device's radiation detector based on thermoelectric cooler.

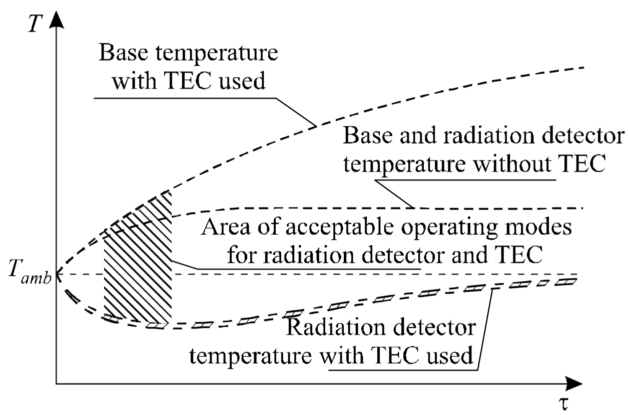

Fig. 2. Dynamics of temperature variation of thermal stabilization elements of IR imaging device's radiation detector in operation of the product.

2.2. Independent medium-temperature combined coolers

In the context of in-depth modernization of special aircraft IR equipment aimed at using intensive kinetic heating under long-term conditions, a combined cooling system based on the Ranque-Hilsch and Peltier effects (hereinafter combined cooling – ram air system) was created. Introduced into a product equipped with a supplementary air intake device, the combined cooling – ram air system (Fig. 3) consists of a four-stage radiation detector's TEC, two-stage system of vortex tubes and special thermal bridges. The vortex tubes are powered from the velocity head of ram atmospheric air. Cooling system solves thermostatting problems at the admissible level of:

– thermally stressed units of the product's optico-mechanical block (OMB);
– base of radiation detector comprising an embedded four-stage TEC ($P \leq 4.2$ W at $I_{oper} \leq 1.2$ A) and creating $\Delta T = 117$ K at $T_{amb} = 333$ K.

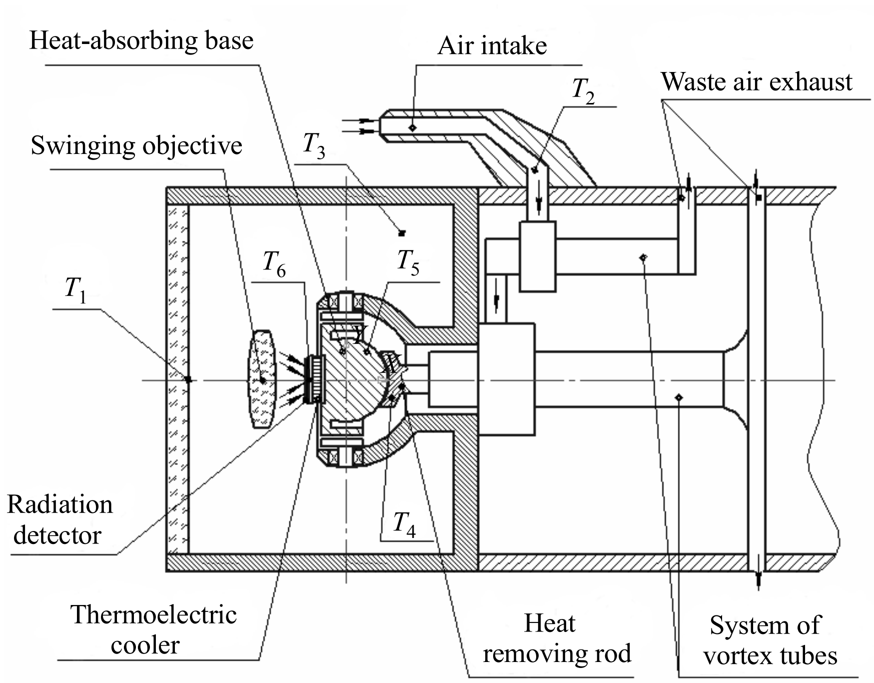

Fig. 3. Basic diagram of cooling system of IR imaging device's radiation detector based on thermoelectric cooler and a system of vortex tubes.

In conformity with the requirements to product operation, its optical system and radiation detector are located in a sealed compartment filled with a non-condensed gas medium. This creates a problem with assuring the necessary thermal operating conditions for the block elements. In the design of a thermostatted compartment proposed in this study, thermal bridges connect the sealed volume of compartment and the unsealed block accommodating heat sinks of thermal bridges blown by atmospheric air cooled in vortex tubes.

As a result of flight tests of thermal breadboard of created product (Fig. 4) it has been established that the temperature of stagnated ram flow reaches 310 to 330 K under long-term operating conditions and 420 to 430 K under short-term intensive operation conditions. In so doing, the vortex stage of combined cooling – ram air system assures temperature reduction of optical system and radiation detector base arranged in a sealed compartment up to 310 to 330 K. Thermoelectric cooler of radiation detector stabilizes its sensitive elements at the level of ~ 200 to 210 K, providing for the required product sensitivity value.

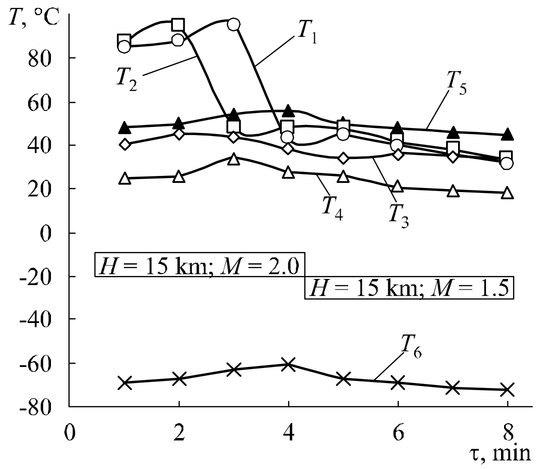

Fig. 4. Dynamics of temperature variation of thermal stabilization elements of IR imaging device's radiation detector in different operating conditions.
T_1 – meniscus temperature.
T_2 – incoming air temperature.
T_3 – temperature inside compartment.
T_4 – heat sink temperature.
T_5 – base temperature.
T_6 – design temperature of cold junctions.

The combined cooling – ram air system was created in cooperation with a series of enterprises of Russian Federation, specialists of Samara State Aerospace University (Samara, Russian Federation) and Thermion Company (Odessa).

Due to intensification of efforts aimed at creating products with cryocooled radiation detectors, no engineering solutions on combined cooling – ram air system were adopted into the enterprise projects.

2.3. Self-contained combined bottled cryocooler of increased service life

As applied to the enterprise IR projects, the problem of cryostatting modern radiation detectors for a spectral range of 5 – 8 μm has been successfully solved since the 60-s by creating bottled throttling microcryogenic systems (MCS). Bottled MCS (Fig. 5) are characterized by a high degree of operation reliability of all elements, the possibility of introducing a throttling microcooler directly into sealed OMB with cryostatting the radiation detector's sensitive element. This assures most rational use of the energy of gas, the noncondensed cryoagent stored in a high-pressure bottle (up to 35.0 MPa).

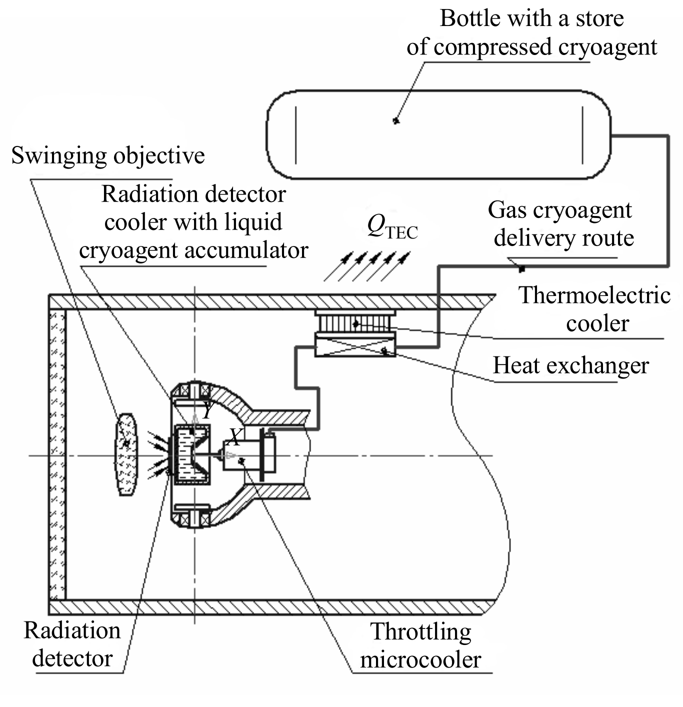

Fig. 5. Basic diagram of economically efficient throttling bottled system for raditiation detector cooling (with a preliminary stage for cryoagent cooling based on thermoelectric cooler).

Depending on the requirements to temporal conditions of product operation and the available volumetric restrictions on OMB, the microcoolers of MCS are designed in refrigerating or liquefying versions.

To realize the required operation duration of a MCS complete with a bottle of assigned volume-mass characteristics, the enterprise specialists create and successfully introduce special microcooler designs. Thus, introduction into the bulk of a small-size microcooler (heat exchanger diameter ≤ 6 mm) of a thermosensitive system based on material with "shape memory" assured the possibility of its operation in the mode of self-regulated cooling capacity.

The operating efficiency of throttling MCS is essentially dependent on the value of cryoagent isothermal throttling effect Δi_T [3]. With cryoagent temperature reduction at microcooler inlet, Δi_T increases in proportion to gas ΔT_{in}.

Introduction of a heat exchanger cooled by thermoelectric cooling system into the route of cryoagent delivery to microcooler further increases the energy resource of gas stored in the bottle. Design of MCS – TEC takes into account the required cooling capacity of thermoelectric cooling system, conditions of its arrangement in the product and removal of thermal energy ($Q_0 + W_{TEC}$) to the environment (here W_{TEC} is electric power consumed by TEC system).

Fig. 6 represents a thermodynamic model and a basic diagram of economically efficient MCS based on a microcooler with an embedded self-regulated throttling unit.

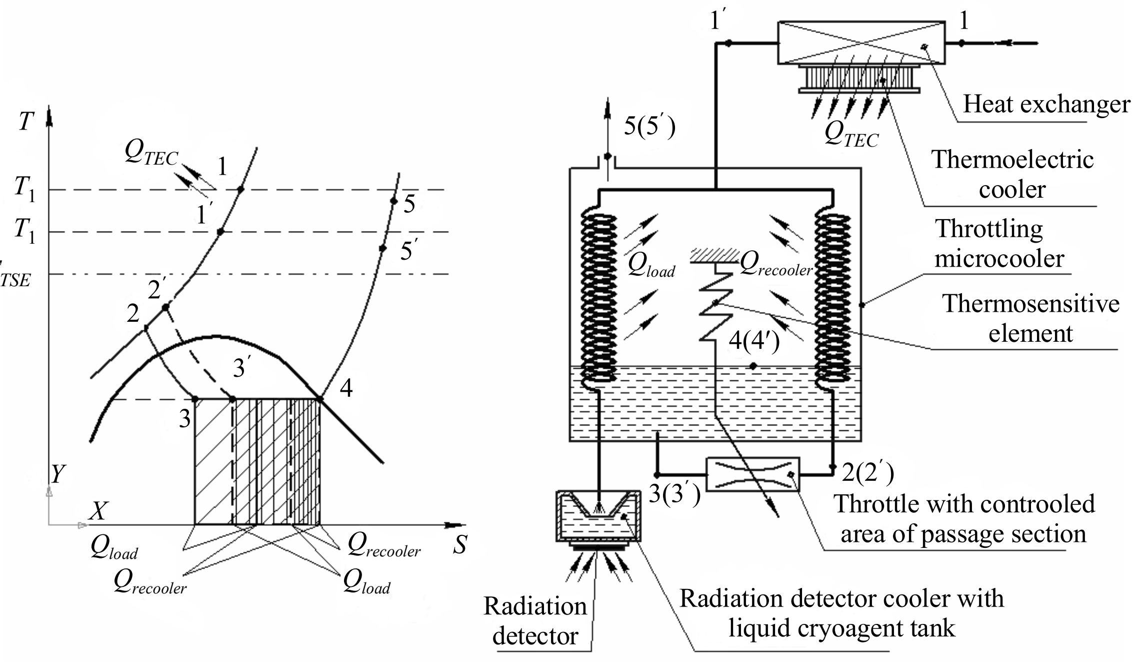

Fig. 6. Thermodynamic operating model of economically efficient throttling bottled system for raditiation detector cooling (with a preliminary stage for cryoagent cooling based on thermoelectric cooler).

The results of experimental investigation of a product complete with MCS-TEC showed system service life increase by 30 – 40% on cooling cryoagent flow (nitrogen) by 25 – 30 K. The TEC system is composed of 4 special modules Altec EBRI.432211.016 (produced by Institute of Thermoelectricity, Chernivtsi). The system consumes $P_\Sigma = 33.8$ W in the circuit of 5.2 V. Heat from the system is removed to ram air flowing around the external product package through structural-technological thermal bridge.

2.4. Self-contained system based on thermoelectric power converter for continuous thermal calibration of two reference IR radiators and thermal protection of IR radiation detector cryostatted by gas cryogenic machine

A quasi-stationary product developed by the enterprise for a continuous selection of observed object by its IR radiation in the range of 8 – 12 μm in the presence of various thermal noises employs [4] a two-level thermoelectric system assuring:

– thermal protection of electric engine of gas cryogenic machine cryostatting radiation detector's sensitive element at the level of 80 K;
– the required rates of temperature change for two small-size reference radiators working in anti-phase modes.

Single-block cryocooler K508 of "RICOR" company (Fig. 7), as part of device being developed, consumes from 13 to 7.5 W in 23 V circuit. In so doing, under critical conditions of its application it is necessary to assure thermal protection of electric engine with $\Delta T \leq 35$ K. We have created a system of active thermal protection based on two types of solid-state thermoelectric converters. In so doing, thermoelectric cooling module Altec-71-1.4×1.4×1.5 solves the problem of thermostatting the electric engine of machine cryocooler. The required rate of temperature change for calibrators in the ranges $T_h = 305 – 345$ K and $T_c = 225 – 260$ K with a change in ambient temperature $T_{amb} = 223 – 333$ K is assured by using modules Altec-7-1.2×1.5×1.5 (size 8 × 8 × 4 mm) in the amount of 1 piece/calibrator. The modules consume up to 3 W of electric power in 12 V circuit; in the process, 5 W of thermal energy is removed from the hot heat sink. To prevent from hoar frost formation on the operating surfaces of calibrators, the device volume is filled with nitrogen dried to dew point temperature not higher than minus 40°C.

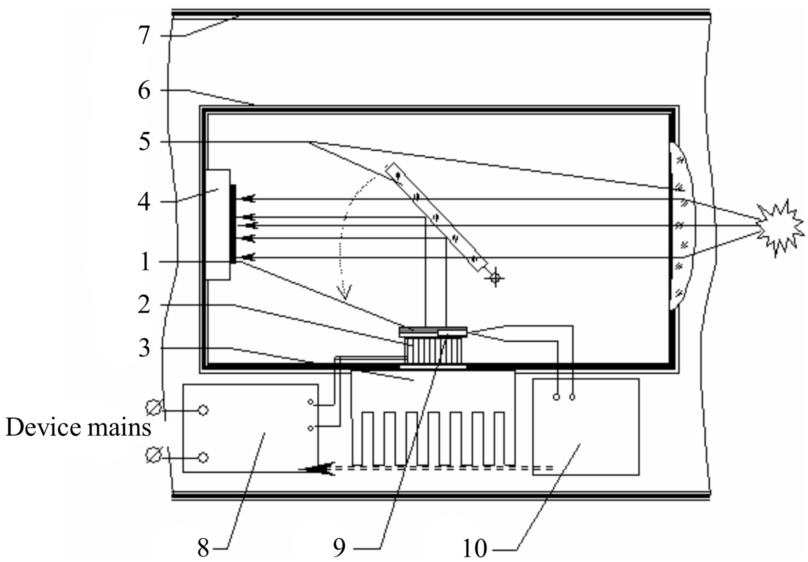

Fig. 7. Basic diagram of self-contained reference radiation source and schematic of its installation in the device. 1 – heat sink, 2 – thermoelectric module, 3 – heat sink, 4 – photodetector, 5 – optical system, 6 – collimator, 7 – device package, 8 – control unit, 9 – temperature sensor, 10 – temperature selector.

2.5. Self-contained system of gas flow cooling

Our enterprise together with "Parallax" scientific-production firm (Kyiv) is creating a small-size installation to prepare cryoagent from the ambient air for throttling microcryogenic systems.

Thermoelectric system (Fig. 8), forming part of the installation, simultaneously in two installation blocks cools by ~ 25 K and ~ 30 K, respectively, a high-pressure transit gas flow (flow rate 100 nl/min, P = 33.0 MPa). Based on the requirements to the operating capacity of the installation in the field conditions, to the value of heat flow removed from thermoelectric system (1.5 kW) providing cooling capacity 0.2 kW in each block, a self-contained system of gas flow cooling has been created.

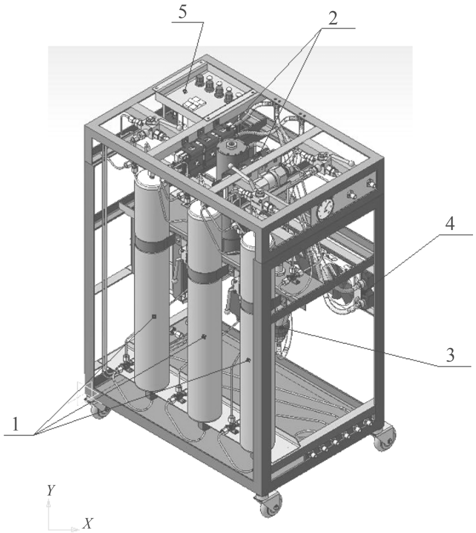

Fig. 8. Small-size installation for preparation of cryoagent from compressed air. 1 – filters-adsorbers; 2 – thermoelectric gas cooling units; 3 – circulation pump; 4 – active water-air heat exchanger; 5 – power supply.

A self-contained gas flow cooling system is a two-circuit system comprising gas heat exchangers cooled by the first stage of TEC and a circuit of active water heat removal therefrom. The circuit includes: the second stage of TEC and water-air heat sinks removing the total heat flow of the system (1.5 kW) to the environment. The system represented in Fig. 4, is based on thermoelectric modules 71-1.5×1.5. There are 4 modules installed in each gas heat exchanger (Fig. 9), and 6 modules are part of the water-air heat sink. The system is powered from the circuit 27 V and 35 V with the operating mode 3.0 A and 4.5 A, respectively, for the modules of gas heat exchangers and for the modules of water-air heat sink.

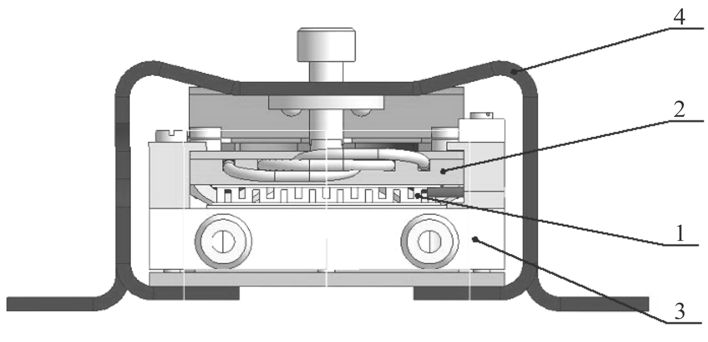

Fig. 9. Gas cooling thermoelectric units. 1 – thermoelectric modules; 2 – gas heat exchanger; 3 – water heat exchanger; 4 – hold-down.

The total energy consumption of the system (14 thermoelectric modules and a hydraulic pump) is ~ 0.6 kW in the circuit 27 … 35 V.

2.6. Electric generator based on thermoelectric converter and vortex tube (Fig. 10)

As applied to problem of electric power supply to technological devices of gas industry, a concept of self-contained power supply system for FLOWTEC complex based on ingenious thermoelectric generator has been developed. The source of "heat" and "cold" in the generator proposed in this study is a vortex tube converting the energy of compressed natural gas into thermal energy in the process of its reduction, for instance, at gas-distributing stations.

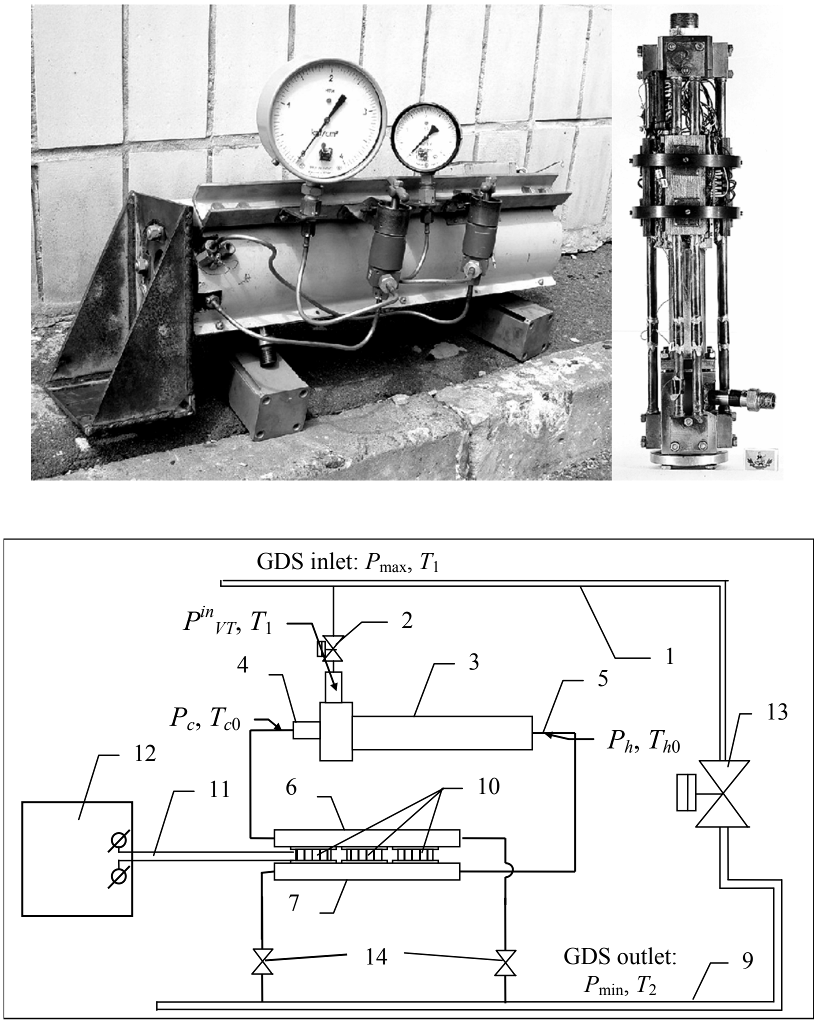

Fig. 10. Appearance, unpacked view and arrangement of combined electric generator as part of gas-distributing station. 1 – high pressure gas mains; 2 – control valve; 3 – dividing counterflow vortex tube; 4 – vortex tube cold flow collector; 5 – vortex tube hot flow collector; 6 – "cold" heat exchanger; 7 – "hot" heat exchanger; 9 – low pressure mains; 10 – thermoelectric modules; 11 – connecting cable; 12 – electric energy consumer; 13 – standard control valve; 14 – valve.

The generator proposed in this study has good prospects due to:

- economic efficiency (does not require gas combustion, is easy to operate);
- reliability (has no moving parts);
- long service life (determined by the service life of thermoelectric modules – at least 5 years of continuous operation);
- electrical and explosion safety;
- possibility of design optimization for specific electric energy consumer.

For electric power supply to gas assessment complex "FLOWTEC" and gas-distributing station automatics, a thermoelectric generator TEG 14/06 (rated power 10 W in the circuit of 14 V direct current) has been developed, manufactured and full-scale tested. The generator is based on a cooled vortex tube of size 32 mm and a system of 16 thermoelectric modules of the type MT2-127-1.6.

The results of experimental studies [5, 6] have shown:

– electric generator TEG 14/06 is functional under conditions of gas-distributing station with the year-round continuous operation;
– operating characteristics of TEG 14/06 (U = 14 V, I = 0.6 A), controllable in the average ranges of change in operating gas parameters, namely inlet pressure P_1 = (14 ± 3) atm and outlet pressure P_0 = (3 ± 1) atm, meet technical requirements to electric power supply of “FLOWTEC” complex.

2.7. Medical cryodestructor

At the request of the enterprise clinic specialists, in 2008 we elaborated “Morozko-2” instrument intended for cooling portions of skin of a biological object when making complicated intramuscular injections.

The instrument consists of a contact plate (see Fig. 11 position 1) cooled by thermoelectric module (2) whose hot junctions are cooled by a “cooler” (3 – aluminium heat sink equipped with a fan). The instrument has a handle (4) and a power cord (5). The power cord ends in a plug (6) with a lateral wire (7) for connection of two supply units.

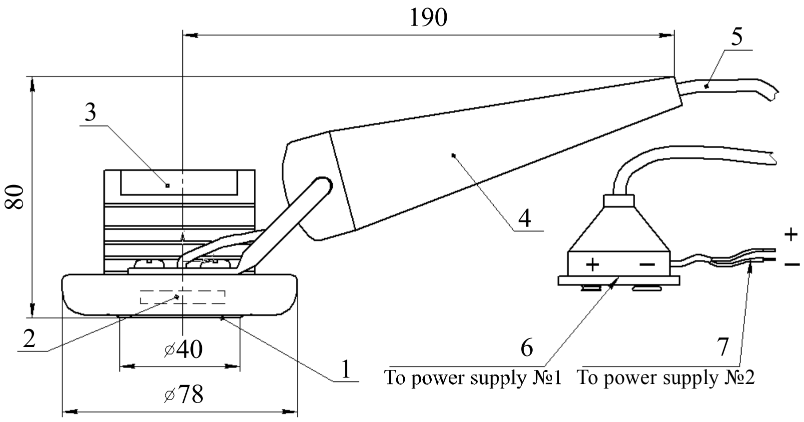

Fig. 11. Basic diagram of thermoapplicator: 1 – contact plate; 2 – thermoelectric module; 3 – heat sink with a fan (“cooler”); 4 – handle; 5 – power cord, 6 – thermoelectric module power plug, 7 – fan power cord.

The instrument allows quick (2 – 3 min) local cooling of skin to +2.4°C on a portion of diameter 40mm and making injections without pain sensations for patient.

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