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Metrological assurance of the sun energy collector testing

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Abstract

In this paper we present the accuracy analysis of energy and temperature measurements for testing and productivity improvement of solar collectors. There are presented possibilities of accuracy and resolution increase of solar energetic luminance sensors. The radiometer with electrical substitution was used in the research. The calibration procedure of the radiometer is described. A mathematical model of conversion function for both temperature and temperature difference measurement was developed as well.

Keywords: solar energy collectors, metrological assurance, radiometers, temperature difference precision measurement.

Badania i pomiary parametrów kolektorów energii słonecznej

Streszczenie

W pracy przedstawiono analizę dokładności pomiaru energii słonecznej i temperatury za pomocą radiometrów z elektrycznym zrównoważeniem. W celu zwiększenia dokładności oraz rozdzielczości radiometrów zaproponowano zastosowanie połączonych równołegle miniaturowych sensorów diodowych do pomiaru różnicy temperatury powierzchni absorbującej kolektora słonecznego oraz otoczenia. Dodatkowo, diody te wykorzystano do nagrzewania sensora w czasie kompensowania. Pokazano, że taka konstrukcja sensora radiometrycznego pozwala odtwarzać temperaturę powierzchni przejmującej. Wykazano, że adytywne i multiplikatywne składniki błędów spowodowane rozrzutami technologicznymi napięć początkowych oraz prądów pomiarowych sensorów diodowych mogą być zmniejszone około $\sqrt{2n}$ razy, przy jednoczesnym zwiększeniu czułości w n razy, gdzie n jest liczbą równolegle połączonych diod. Opisano procedurę kalibracji radiometru przy zerowej i bliskiej maksymalnej mocy promieniowania. W pierwszym przypadku można skorygować addytywny, a w drugim – większość multiplikatywnych składników błędu. Zaproponowano schemat blokowy przyrządu do precyzyjnych pomiarów różnicy temperatury. Zastosowano wielokanałowe mierniki rezystancji z platynowymi sensorami temperatury. Do kalibrowania miernika różnicy temperatury wykorzystano precyzyjne miniaturowe rezystory, a do kalibrowania całego toru pomiarowego użyto precyzyjny termostat sterowany programowo. Opisano także konstrukcję stanowiska do pomiarów parametrów kolektorów słonecznych w laboratorium badawczym w Narodowym Uniwersytecie „Lwowska Politechnika".

Słowa kluczowe: kolektory energii słonecznej, radiometry, precyzyjne pomiary różnicy temperatury, pomiary przepływu.

1. Introduction

Nowadays the problem of solar energy is a key issue and more than ever solar converters, especially collectors, appear on the market. Under these circumstances there is a need in on-the-spot checks of key technical parameters to ensure the optimal choice of the consumer in terms of the cost and quality.

Currently metrological assurance of solar collectors tests is based on a set of ISO standards ISO 9459, ISO 9806.

Control equipment for measurements of solar and thermal radiation, temperature and temperature difference according to these standards ISO 9846 and ISO 9847 requires rather labor-consuming calibration procedure.

One of these fundamental defects is periodic calibration of radiation receivers on solar sensitivity within the calendar year, whose changes must not exceed ±1%, otherwise additional frequent calibrations are necessary or also replacement of the device that requires significant economic and resource costs.

All the mentioned above facts show the importance of regular metrological works focused on search of possible ways of further development, cost-cutting methods and means of measurements of solar radiation parameters.

2. Analysis of the basic requirements of solar collector testing

Solar collectors (SC) may be tested under conditions that are close to operating at their sun exposure or in vitro using simulators. In respect to the comparison between the SC characteristics important for a consumer then, obviously, it is easier and less expensive to ensure implementation of metrological requirements of normative documents ISO 9806. During laboratory tests the following technical parameters SC were inspected: definition of the flux per unit area of heat emission in the space and in simulators of solar radiation flux within the range of 1000 W/m^2 with a margin error not exceeding ± 10 kW/m^2; temperatures (it is necessary to execute three temperature measurements: t_{in} – liquid temperature of the collector input, t_{out} – liquid temperature of the collector output and t_a – ambient temperature (required accuracy and environmental conditions for these measurements are different, so the converter and auxiliary equipment can also be different); liquid coolant temperature differences ΔT which an error of estimation differences between the input and output collectors temperatures ΔT at most ±0,1 *K*; liquid flow rate in the collector with an error no greater than ±1,0*%* of measured value; the test interval with an error no greater than ±0,1*%*. The measurement error of input and output liquid coolant temperatures in the whole range 0^0C to 100^0C shall not exceed ±0,1^0C, however, as an assurance that temperature does not change with time, there is a need of much higher resolution of the temperature signal measuring device - to ±0.02^0C.

The analysis of the presented requirements shows that one of the main problems in the construction of test facilities for solar collectors is to provide the necessary accuracy and sensitivity of receiver thermal radiation. It is known that sufficiently high metrological parameters during measurement of the thermal radiation flux can be achieved using an absolute radiometer or an electrical substitution radiometer.

Really neglecting correction due to various losses, this equivalence of temperature T implies that the optical power Φ is equal to the electrical power $P=I^2R$ [1]. Devices using this principle today are of fundamental importance in radiometry and their modern application for sun collectors testing is discussed in [2]. A more detailed analysis of electrical substitution radiometer metrological properties shows that, substantially, they are limited by the insignificant electric sensitivity of modern designs of radiometers.

On the other hand, a significant contribution to the resulting error makes geometric spatial dissimilarity of the location of temperature sensitive and heating elements. Taking this into account, we suggest using both sensitive and heating elements of surface mounting transistors to reduce these errors, which due to small overall dimensions and weight can be evenly located on the solar radiance receiver surface. They have high temporal stability in a room temperatures (at several hundredths of a kelvin within a year). [3, 4] Thus point-by-point measurements in the first approximation are replaced by a measurement of the temperature integral value of the receiving surface with subsequent of their averaging [5].

The undeniable advantages of diode temperature transducers (DT) are: high sensitivity, long-term stability, low inertia, rather small nonlinearity, quite wide temperature range of use, the possibility of temperature point measurements, low cost and ease of fabrication [3-5]. The absolute measurement error of temperature difference $\Delta\Delta\Theta x$ is given by

$$\Delta\Delta\Theta_X = T_{0n}\left(\delta_{U0Ci} - \delta_{U0Cj}\right) + T_{0n}\left(\frac{\Theta_{X1}}{T_0}\delta_{U0Ci} - \frac{\Theta_{X2}}{T_0}\delta_{U0Cj}\right) - \\ - T_{0n}\frac{\varphi_0}{U_{0H}}\left(\frac{T_{X1}}{T_0}\delta_{S0Ci} - \frac{T_{X2}}{T_0}\delta_{S0Cj}\right), \quad (1)$$

where: $T_{0n} = \frac{U_{0H}}{E_K - U_{0H}} \cdot \left(1 + \frac{\varphi_0}{E_K - U_{0H}}\right) \cdot \frac{T_0}{n}$; $\varphi_0 = kT_0/q$ - *pn* junction temperature potential in temperature T_0; k, q – the Boltzmann constant and electron charge, respectively; E_K – semiconductor band gap; U_{0H} – forward bias voltage drop nominal value for direct current I_d and *pn* junction temperature T_0; $\delta_{U0Ci} = \sum_{i=1}^{n}\delta_{0i}$, $\delta_{U0Cj} = \sum_{j=1}^{n}\delta_{0j}$ - summarized error of forward bias voltage drop value for n series launching *pn* junctions, one has a temperature T_{X1} and the other - T_{X2}; $\Theta_{X1} = T_{X1} - T_0$; $\Theta_{X2} = T_{X2} - T_0$; δ_{0i}, δ_{0j} - relative error of U_{0i} and U_{0j} forward bias voltage drop value for numbers i and j *pn* junction which have temperature T_{X1} and T_{X2}, accordingly; $\delta_{S0Ci} = \sum_{i=1}^{n}\delta_{S0i}$, $\delta_{S0Cj} = \sum_{i=1}^{n}\delta_{S0j}$ - summarized error of forward bias heat current value for n series launching *pn* junction one has a temperature T_{X1} and the other - T_{X2}; δ_{S0i}, δ_{S0j} - relative error of U_{0i} and U_{0j} forward bias voltage drop value for numbers i and j *pn* junction which have temperature T_{X1} and T_{X2} accordingly.

Ratio (1) analysis shows that it is expedient to use DT made in the same technological cycle for the temperatures difference measuring instrument realization. This additive error component caused by variations in the initial voltage decreases $\sqrt{2n}$ times. The multiplicative component measurement error decreases at $\sqrt{n}$ times (second and third components of (1)), while its other part that depends on the reverse currents values spread of DT decreases also in $\sqrt{2n}$ times and other multiplicative error components do not undergo any changes.

In the manufacturing process it is possible to correct values of both additive and multiplicative error components at two temperature values. To correct the additive error component, a useful arbitrary temperature for example is equal to the ambient temperature. It is a good practice to use a standard radiator for the multiplicative component error correction.

3. Possibilities of improvement of temperature and temperature difference measuring device

It is obvious that for precision measurements of temperature and a difference of temperatures during solar collector tests it is necessary to use thermometers to meet the requirements of normative documents with a platinum resistance temperature detector (RTD). But the problem of increasing the accuracy of such thermometers comes up immediately, because the error limit level of the most accurate RTD class A is ±0,15 *K*, but during the tests desirable error has to be ±0,02 *K* for ISO 9806 requirement. Note that the easiest method to improve the accuracy by the RTD parameter selection is at the same time labor-consuming and costly for application in practice. Another method of evaluation and RTD allowance consideration is not less labor-consuming and requires the use of precision equipment.

Indeed, the control of the absolute error of a resistance temperature detector is carried out by means of precision equipment based on a null and steam thermostat, stabilization and value measurement of the RTD measuring current and calculating the RTD resistance measured value. If it has the null and the steam thermostat and also the thermostat, it can reproduce stable but not absolutely precise the temperature value midway between the triple point and the boiling water temperature. RTD resistance values are measured at these three temperatures. From the resulting system of three equation there are calculated resistance R_0 at 0^0C and *A, B* coefficients of resistance temperature dependence.

In practice there is a useful method based on reference RTD implementation, which uses inside a thermostat with stable but not so precisely known temperature values and a digital ohmmeter or a thermometer, the output of which is connected to a control device such as a personal computer or microprocessor controller [7].

The used nowadays units, such as a TCP-0105 HO type digital liquid thermostat which has the thermostat control range $(0…100)^0$C, $0{,}01^0$C temperature value input increment, limit value of basic measurement error and reproduction temperature $\pm 0{,}02^0$C and the remote control possibility, came in premises of significant simplification of the RTD test automation procedure [8].

The main disadvantage of the above presented methods of RTD metrological checks is non-automatic mode reducing its productivity and objectivity. Preliminary analysis shows that the structure based on the multi channel ohmmeter will have this set of best metrological characteristics [7].

During calibration the temperature measurement error value should be monitored several times more precisely than the admissible value limit of the errors [8]. Given the temperature maintaining error in the thermostat, the temperature measurement error value in the range $(0…100)^0$C for RTD Pt 1000 class «A» shouldn't exceed $\pm[(0{,}01…0{,}03)…(0{,}07…0{,}12)]^0$C, or ±[(0,04…0,12) … (0,40…0,68)] Ohm, or ±[(0,004…0,01) … (0,03…0,05)]%. Such high requirements for precise measurements of RTD electrical resistance R_x require the use of a special multichannel precision ohmmeter.

To meet the mentioned above requirements, there was developed a multi-channel precision ohmmeter based on four wire connection of measurable resistors $R_{X1},… R_{Xn}$, method of AEC adjustment with with modulation of measuring currents of I_1 and I_2 [9, 10] whose block diagram is shown in Fig. 1. A modulation current generator (CG) was realized on an operating amplifier basis (OA) DA1, which was covered by negative feedback through the load resistance and the current specified resistor R_N [10].

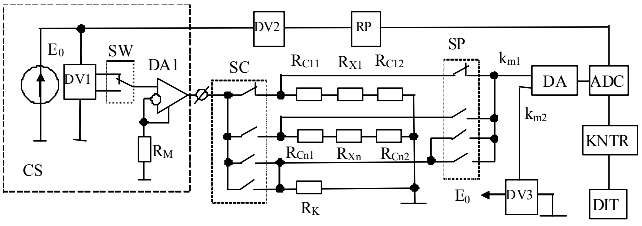

Fig. 1. Block diagram of the multi channel precision ohmmeter to test resistance temperature detector

Rys. 1. Schemat blokowy wielokanałowego omomierza do badania rezystancyjnych czujników temperatury

A modulation voltage is formed by dividing the reference voltage E_0 by a divider and alternate connection of its outputs via switch SW to input of OA DA1. Each of the n double wire measuring resistors R_{X1}, ..., R_{Xn} are alternately connected by n-input switch channels SC, SP to the current conductors couple and to the DO input. Minor values of commutate measuring currents and voltage drops on RTD allow selecting a CMOS switch for implementation of the current SC and the SP potential switches. In addition, lack of a commutate metering circuit of residual voltages gives a possibility to implement switches with a minor value error [9, 10].

The currents of reverse switches can cause great errors in value in case of resistance measurement of R_{X1}... R_{Xn}. However, by means of metering circuit commutation the error value is adjusted. Measurements are taken in two cycles of transformation N_{X11}, N_{X12} and N_{X21}, N_{X22}. Measurement result codes N_{Xj} of R_{Xj} resistance we shall find in [9, 10]

$$N_{X11} = \frac{k_{ADC}}{E_0} \cdot \frac{k_{m1} r_{XC1}\left(m_1 E_0 + \Delta_1\right) - k_{m2} p E_0 + \Delta_A + \Delta_{KMT1}}{1 + \Delta_{PB}/E_0 k_0}, \quad (2)$$

$$N_{X12} = \frac{k_{ADC}}{E_0} \cdot \frac{k_{m1} r_{XC1}\left(m_2 E_0 + \Delta_1\right) - k_{m2} p E_0 + \Delta_A + \Delta_{KMT1}}{1 + \Delta_{PB}/E_0 k_0}, \quad (3)$$

$$N_{X21} = \frac{k_{ADC}}{E_0} \cdot \frac{k_{m1} r_{XC2}\left(m_1 E_0 + \Delta_1\right) - k_{m2} p E_0 + \Delta_A + \Delta_{KMT2}}{1 + \Delta_{PB}/E_0 k_0}, \quad (4)$$

$$N_{X22} = \frac{k_{ADC}}{E_0} \cdot \frac{k_{m1} r_{XC2}\left(m_2 E_0 + \Delta_1\right) - k_{m2} p E_0 + \Delta_A + \Delta_{KMT2}}{1 + \Delta_{PB}/E_0 k_0}, \quad (5)$$

where: $r_{XC1} = R_{X1} + R_{C11} + R_{C12}/R_M$; $r_{XC2} = R_{X2} + R_{C21} + R_{C22}/R_M$; R_{Xj} – the measured resistance value in the *j* closed channel; $\Delta_{KMT1} = \left(I_{B11234} + I_{CC} + I_{B21234}\right)R_{XC1} + I_{B11234}R_{\kappa 11} + I_{B21234}R_{\kappa 21}$ $\Delta_{KMT2} = I_{B11234}R_{XC2} + I_{B11234}R_{\kappa 12} + I_{B21234}R_{\kappa 22}$ - equivalent AEC of DO; $R_{XC1} = R_{X1} + R_{C11} + R_{C12}$; $R_{XC2} = R_{X2} + R_{C21} + R_{C22}$; $I_{B11234} = I_{B11} + I_{B12} + I_{B13} + I_{B14}$; $I_{B21234} = I_{B21} + I_{B22} + I_{B23} + I_{B24}$; $I_{CC} = I_{C11} + I_{C21}$;; I_{C11}, I_{C12}, I_{C21}, I_{C22} – reverse junction current from drain to lining of *j* closed switches SC; I_{B11}, I_{B12}, I_{B13}, I_{B14}, I_{B21}, I_{B22}, I_{B23}, I_{B24} – reverse junction current from a source to lining of *j* closed switches SC; m_1, m_2 – division coefficients of the current-specified divider; k_{m1}, k_{m2} – transfer coefficients of the differential amplifier; E_0 – output voltage of the reference voltage source; k_{ADC} –analog-to-digital converter transfer coefficient (ADC); Δ_{PB} – bias voltage of the reference voltage repeater; Δ_A – the differential amplifier bias voltage DA; *p* - divider PD3 transformation coefficient; k_0 – division coefficient of the reference voltage for ADC.

Codes results of the resistance and their difference measurement shall be found as $N_{X1}=N_{X11}-N_{X12}$, $N_{X2}=N_{X21}-N_{X22}$, $\Delta N_X = N_{X1} - N_{X2} = \frac{k_{ADC}k_{m1}\left(m_1 - m_2\right)}{k_0\left(1 + \Delta_{PB}/E_0 k_0\right)} \cdot \frac{R_{XC1} - R_{XC2}}{R_M}$.

Transforming the code during calibration $\Delta N_K=N_{K1}-N_{K2}$, it is possible to define the scope calibration coefficient $\frac{k_{ADC}k_{m1}\left(m_1 - m_2\right)}{k_0\left(1 + \Delta_{\Pi B}/E_0 k_0\right)} \cdot \frac{1}{R_M} = \frac{\Delta N_K}{R_K}$. Giving this coefficient and true value of the calibration resistor, the corrected value of the result code of measurement of a resistance difference is defined as

$$\Delta N_X = \Delta N_K \left(R_{XC1} - R_{XC2}\right)/R_K . \quad (6)$$

Analysis of expression (6) leads to the conclusion that the result of the resistance measurement does not depend on the ACE calibration tract and switch parameters. The result of the RTD electrical resistance measurement will not depend on the connecting line resistance, and closed switches SC and SP in case of high resistance output of the current generator CG and input resistances and the voltage repeater of the OA DA2.

The DO structure provides the ability to connect two calibration resistors. Periodic measurements of their resistance value and the presented calibration algorithm give a chance to correct MEC and QEC of the developed multi-channel precision ohmmeter.

The precision ohmmeter developed can be implemented using modern microelectronic base and information technologies for a digital data transmission on PC control units. Using modern personal computers and relevant software the designed structure can be employed to automate all measurement procedures during solar collectors testing.

4. Experimental station

As the previous analysis showed, one of the most pressing problems of productivity increasing in the process of solar collector tests is automation of the whole process, including calibration and RTD metrological check tests. In measuring laboratories of "Zaliznychneteploenerho" and the certification body "Lvivpolisert" of the National University "Lviv Polytechnic" (Lviv, Ukraine) the automatic workplace on RTD check on the basis of the precision liquid thermostat TCP-0105-HO and on digital ohmmeter DO-0103 (Fig. 2) have been working for several years [7, 8]. The workplace structure of the RDT metrological check tests includes: digital precision liquid thermostat TCP-0105-HO; testing switch of four-wire line; precision digital ohmmeter DO-0103 connected with the PC via interface RS-232; PC with the Relevant Software.

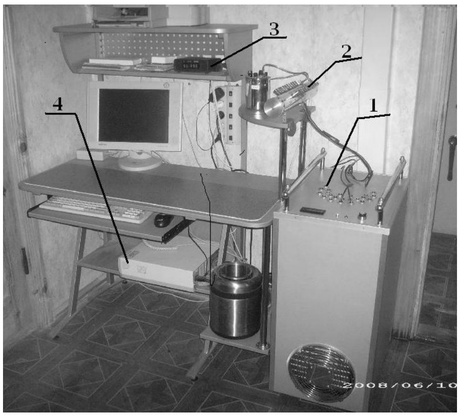

Fig. 2. Workplace of the experimental station on RTD checks of the National University "Lviv Polytechnic"
Rys. 2. Stanowisko laboratoryjne do sprawdzania rezystorów w laboratorium Politechniki Lwowskiej

According to consumers, the most important solar collector parameters is the output efficiency of the energy conversion in the initial energy of the warmed-up liquid. For this purpose, the test laboratory of the National University "Lviv Polytechnic" has designed and manufactured a flow station (Fig. 3). To determine the efficiency output of the solar collectors, it is needed to evaluate radiation power by a radiometer in the center and in the four extreme points of its surface and calculate its average value E_{cp}. The number of the received thermal energy is defined by the flow station over time. Application of such a structure of the automated measuring laboratory except known technical upgrade allows reaching, some more essential practical advantages.

Fig. 3. General view of the solar collector flow station installed in the test laboratory of the National University "Lviv Polytechnic"
Rys. 3. Wygląd ogólny stanowiska przepływomierza do badania kolektorów słonecznych zainstalowanego w laboratorium Politechniki Lwowskiej

5. Conclusions

It is shown that metrological support of solar collectors is quite complicated, since for measurements of solar radiation parameters there is required the test equipment, which needs labour-consuming calibration procedure and depends on both environmental changes and used measurement methods.

It is proved that on the basis of using an absolute radiometer with electrical substitution and body-free semiconductor temperature sensors as well as processing the results of the intermediate conversions on a certain algorithm it is possible to implement devices of difference temperature measurement in the working range with the several hundredths of kelvins.

It almost does not require long-term calibration and a few years of operation may provide some economic benefit. The analysis shows that it is expedient to use the diode sensors made in a uniform technological cycle for implementation of the measuring instrument of a temperatures difference of the thermal radiation receiver.

In order to improve the accuracy and stability and the implementation possibility of precision measuring units, the use of precision platinum RTD Pt1000 is suggested. The developed precision thermometer is based on a multi channel ohmmeter with automatic error correction and measuring tract calibration using a precise programmable controlled thermostat.

It gives possibility to provide practical invariance of the influence of the connection line resistance and also of the error caused by measuring current value as well as the methodical error caused by sensor overheating. In order to improve the thermometer accuracy and stability, the use platinum resistance temperature detector is suggested.

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