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Tungsten–Rhenium Thermocouples Calibration in Ultra-High Temperature Range

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Abstract
There are presented results of experimental research on calibration of tungsten–rhenium thermocouples at the temperatures exceeding the upper limit of measurements (1700 °C) of standard type B thermocouple. The research was carried out using the high-temperature installation UKT-2500 designed for practical use in production of temperature sensors based on refractory thermocouples. Available types of insulating ceramics for thermocouples have been tested in the temperature range of (1500–2500) °C. The effects of signal shunting and thermocouples stability in inert atmosphere have been investigated at upper limit of the operating temperature range. There was proved practical feasibility of the method for calibration of several contact temperature sensors (up to 10) in one run relative to radiation pyrometer readings. Its suitability for thermocouple calibration and certifying of thermocouple wires in the temperature range (1200–2200) °C was shown. Installation enables to use reference fixed-points of Me-C type to get the highest accuracy calibration of a single tungsten–rhenium thermocouple. Type A bare-wire thermocouple was calibrated in the whole measuring range from 1200 °C to 2500 °C against an accurate radiation pyrometer.

Keywords Calibration against a radiation pyrometer · Signal shunting · Thermal EMF stability · Tungsten–rhenium thermocouple · Ultra-high temperature

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1 Introduction

Increasing the efficiency of modern aircraft engines, development of new composite and ceramic materials, metallurgy of refractory metals, nuclear safety issues—require reliable control of working environment temperature in the range (1700–2200) °C and higher, at least for a short time.

The current standards [1–3] provide only one temperature measuring instrument of contact type above 1700 °C—tungsten–rhenium (W–Re) thermocouple. But metrological equipment available in mass production does not allow to calibrate a sensor or its sensitive element for operation at temperatures above 1800 °C, as well as to assess its instability. Separate publications [4] on this topic indicate large thermal EMF drift of thermocouple at ultra-high temperatures. The main objective of this study was to provide the necessary metrological characteristics of temperature sensors, including their calibration against a radiation pyrometer at temperatures above 1700 °C, as well as to check their instability for lifetime. Sensors development within the specified temperature range solves an important technical problem of high-temperature contact thermometry, the results of which can be used in various industries.

2 Experimental Equipment and Procedures

2.1 Sensor Design

For high-temperature applications sensor design is largely determined by technical requirements of customers, and their operating conditions are often unique. Within the specified operating temperature range sensor must have initial calibration, which should be within the tolerance limits from nominal values. Standards define two types of W–Re thermocouples for contact temperature measurements in the range (1700–2300) °C: type A (W-5 %Re verse W-20 %Re thermocouple) and type C (W-5 %Re verse W-26 %Re thermocouple). Type A thermocouple can be used for a short time (~ 1 h) up to the temperature of 2500 °C. The temperature of possible long-term use for type A is limited to 2200 °C. Long-term use is supposed to be of several tens of hours. For this project specimens used were of the simplest construction: two thermoelements insulated by two-bored ceramic tubes, also they can be placed inside a protective tube made of refractory metal. For ultra-high temperature measurements bare-wire thermocouple was used.

2.2 Insulating Ceramics

During the research, insulating properties of several ceramic materials available on the market were tested experimentally. Possible upper limits of operating temperature range for probes with various insulators were established:

- up to 1800 °C for thermocouple insulated with high-purity aluminum oxide Al_2O_3 99,7 %;
- up to 1700 °C or 1900 °C for thermocouple insulated with hexagonal or pyrolytic boron nitride (BN), respectively;
- up to 1950 °C for thermocouple insulated with monocrystalline Al_2O_3 tubes (sapphire);
- up to 2200 °C for thermocouple insulated with hafnium or magnesium oxide (HfO_2 or MgO of high purity).

At the same time, it should be noted that hexagonal boron nitride (98 % purity), having high operating temperature, showed sharp decrease in the insulation resistance value already at the temperature of 1700 °C, pyrolytic boron nitride with the purity of 99.995 % was operable up to 1800 °C, and pyrolytic boron nitride of the highest quality (99.999 %) worked only up to 1900 °C at extremely high cost. In addition, at high temperatures BN chemically reacts with thermoelement wires embrittling them in a few hours to complete breakage of measuring circuit. Finally, boron nitride of any structure was excluded from consideration as an electrical insulator of W–Re thermocouples. Almost all nitrides and carbides become semiconductors at ultra-high temperatures.

Hafnium oxide with the purity of 99.98 % (including $ZrO_2 < 1$ %), having not the best electrical insulation properties at low (less than 1500 °C) temperatures, turned out to be quite operable up to the temperature of 2200 °C. Magnesium oxide with a purity of 99.4 % also showed its operability up to 2200 °C. At this temperature the effect of signal shunting (reduction) by (15–20) degrees have already been observed. Its application in vacuum might be limited by high vapor pressure of MgO relative to other ceramics and more chemical activity at high temperatures.

The above-mentioned application limits may decrease for sensor insulators in protective tubes made of refractory metals because of possible interaction between the sensor structural elements [5]. Materials compatibility and their purity are of great importance for a probe lifetime.

All tests were carried out in inert atmosphere (argon purity 99.993 vol. %) in presence of negligible quantities of carbon which can enter inside protective tube from working space of the furnace through holes at upper (cold) part of the tube.

2.3 Equipment and Scheme for Thermocouple Calibration

As a part of the project, special installation based on the high-temperature BB3500YY furnace was developed. The furnace realizes temperatures in the operating range (1000–3500) °C for calibration of radiation pyrometers and has positive feedback from the world's leading laboratories (NIST, PTB, LNE, NIMJ, NIM of China). However, the furnace design required significant refinement for calibration of contact temperature sensors. Thermocouple calibration in the furnace was carried out against the readings of a reference radiation pyrometer (Fig. 1).

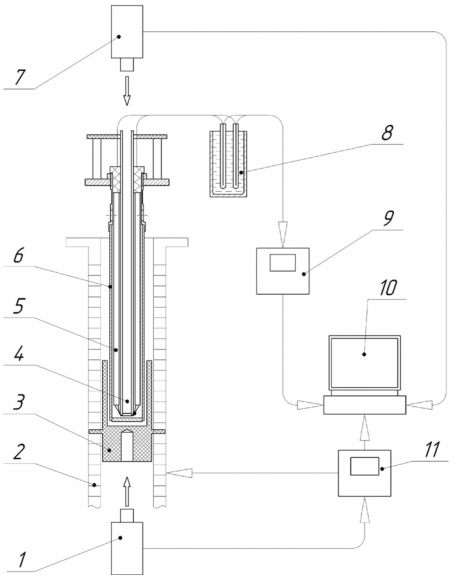


Fig. 1 Measuring scheme of thermocouples calibration against the readings of a reference radiation pyrometer. 1—feedback pyrometer for the furnace heating control; 2—tubular electric heater consisting of graphite rings pile; 3—radiation block forming the working area of the furnace; 4—carrier tube with thermocouples and central cavity for sighting reference pyrometer; 5—thermocouples being calibrated inside two-bored insulators; 6—outer protective tube of thermocouple assembly; 7—reference radiation pyrometer; 8—thermostat for cold junctions of thermocouples; 9—battery-powered millivoltmeter; 10—control computer of the installation; 11—device for the furnace temperature control and managing by heating/cooling process

Taking into account the fact that material of the furnace heating element is graphite, additional protection of insulating materials and thermocouple wires in carburizing atmosphere was required.

Basic requirement for calibration of contact temperature sensors is presence of uniform temperature field in working zone. For the used furnace, zone's uniformity is determined by design of the graphite heater (Fig. 1). It represents itself a column of graphite rings (2) and diaphragms limiting the radiation flux from the working space of the furnace. At working zone radiation block (3) is placed. Thermocouple assembly (5) protected by outer tube (6) was immersed to the cavity of radiation block. Calibrated thermocouples were attached to the end of central carrier tube (4). Both tubes were made of tungsten. Internal surface of bottom plug at the end of central tube was the source of radiation to determine the reference temperature of thermocouple assembly.

Measuring and electric circuits of millivoltmeters and power supply of the installation were separated to exclude possible inducing of electric potential in measuring circuit at high temperatures.

A few tests with different columns of graphite rings and sufficient number of diaphragms ensured axial temperature uniformity inside the working zone.

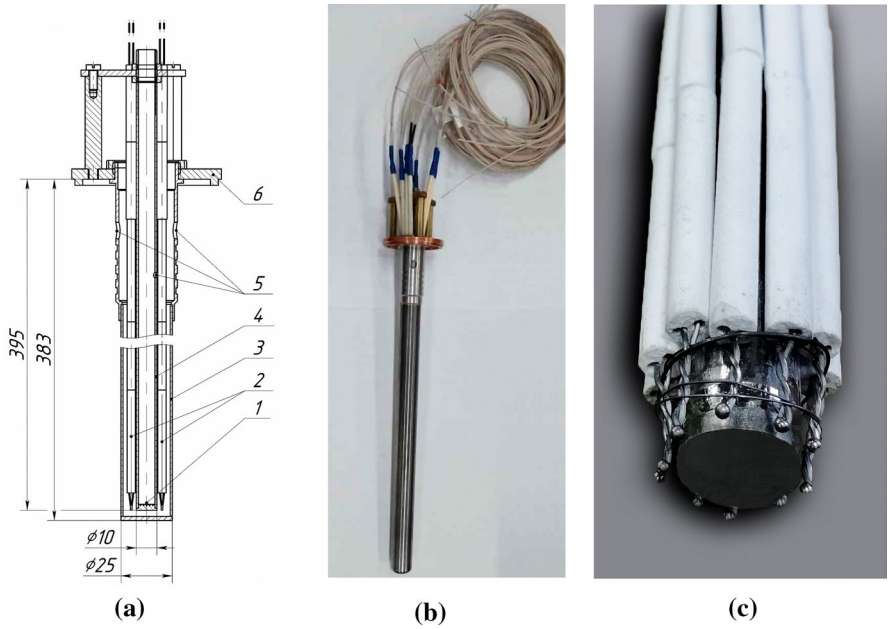


Fig. 2 Thermocouple assembly (a) in protective tungsten tube (b) [6] and thermocouples location around central carrier tube (c). To the tube bottom plug a reference pyrometer was sighted. 1—radiating plug; 2—thermocouples; 3—outer protective tube; 4—carrier tube; 5—inlets of inert gas; 6—mounting flange

Temperature difference at 50 mm height from the bottom of the central tube carrying thermocouple assembly (Fig. 2a) was within ± 1.0 degree at 2000 °C. Wall of the radiation block had the height of 70 mm, equalizing temperature field, and created the working area for temperature measurements. The bottom plug (1) of the central tube (4) had profiled surface to dissipate radiation inside the tube. Radiating cavity at the height of 50 mm was practically isothermal, and it was close to the black body. Nevertheless, the cavity wasn't so perfect due to heat losses because of radiation to outside and thermal conductivity of its walls.

Azimuthal temperature non-uniformity in measurement zone of the thermocouple assembly (Fig. 2b) was estimated from the readings of 10 thermocouples installed along the circumference of the carrier tube (Fig. 2c). All thermocouples of the same type were made of the same batch of thermocouple wires. After furnace temperature stabilization simultaneous readings of all temperature recorders gave real information about azimuthal irregularity, which at the temperature level of 2000 °C did not exceed (4–5) degrees in circumference, or ± 2.5 K. The thermocouple assembly design for simultaneous calibration of several W–Re thermocouples was protected by Russian Federation patent for invention [6], which was registered also as the Patent Cooperation Treaty (PCT) international application.

Vertical design of the furnace and its calibration unit allows you to have reliable filling of all internal cavities with an inert gas. It's difficult to measure temperature of working zone shifting during heating and cooling, when reference pyrometer is sighted on furnace side window [7]. While vertical pyrometer sighting on the bottom

Fig. 3 Installation UKT-2500 for calibration of tungsten–rhenium thermocouples [8]

of open tube overcomes these difficulties. At the same time, there is no intermediate element (glass window) between the pyrometer lens and radiating cavity of central carrier tube, whereas it is present in the constructions [7].

Results of the installation certification (Fig. 3) showed that it reproduced the operating temperature range from 1200 °C to 2200 °C with good accuracy. The maximum deviation from the reproducible temperature value was 3.5 °C at the temperature level of 2200 °C and did not exceed (1.0–2.7) °C at other measurement points.

Calibration of reference pyrometer used against standard black body was carried out with expanded calibration uncertainty not exceeding 3.5 °C in the temperature range from 1000 °C to 2500 °C. When using corrections to the readings of the pyrometer, the relative error of reference temperature measurements did not exceed 0.25 %.

Having combined standard uncertainty of the furnace temperature measurement equal to 2.4 °C at 2000 °C, we evaluated the following uncertainty budget of basic components for type A thermocouple calibration:

- EMF measurement standard uncertainty, 11 μV;
- inhomogeneity of thermoelements [10], 14 μV (axial temperature uniformity ±1 K measured by one thermocouple from radiating plug to 50 mm height confirms this value);
- none uniformity of temperature field, 26 μV;
- furnace temperature standard uncertainty, 25 μV;
- signal shunting was not observed at 2000 °C and below this level with hafnia insulators.

Calculated combined standard uncertainty is 40.2 μV, expanded uncertainty with coefficient k = 2 will be 80,4 μV or 7.7 K for thermocouple sensitivity 10.4 μV/K at 2000 °C. This accuracy is sufficient for calibration of refractory thermocouples.

In the temperature range (600–1700) °C thermocouples were calibrated in air by the usual calibration method [9, 10] of working W–Re thermocouples sealed in sapphire tube against a reference platinum–rhodium type B thermocouple. Calibration

was performed in electric furnace in air. The calibration points of W–Re thermocouples made with reference thermocouple in the temperature range (1200–1700) °C then served as reference points for approving correctness of calibration method with radiation pyrometer at temperatures above 1700 °C.

It's need to note that the heater construction (Fig. 1) can accept a fixed point cell that realizes eutectic melting and solidification points of metal carbides. It can reproduce the fixed point temperature with high accuracy [11–13]. Two fixed-points are suitable for calibration of W–Re- thermocouples with hafnia and sapphire insulators above 1700 °C: Pt–C (~ 1738 °C) and Ru–C (~ 1954 °C). A few researchers [14, 15] presented results of W–Re thermocouple calibration in fixed point cells with good accuracy. Radiation pyrometer used as reference instrument for thermocouples calibration can be also periodically calibrated in such cells.

3 Experimental Procedures and Results

Summary the experimental tests made and description of thermocouple samples utilized in each test is shown in Table 1.

3.1 Stability Test of Thermocouples at the Temperatures of 2000 °C and 2200 °C

To perform stability tests several batches of specimens were manufactured, consisted of five thermocouples of type A and five thermocouples of type C (see Table 1). Thermocouple wires were placed in two-channel ceramic tubes and had open working junction. They were fixed to the central carrier tube of the calibration unit (see Fig. 2c). At the length of 300 mm from working junction thermocouples were insulated with hafnium oxide tubes and further with aluminum oxide tubes. Total immersion depth in all tests was ~ 400 mm.

All specimens were initially calibrated in the temperature range from 1000 °C to 1600 °C against type B reference thermocouple. Thermal EMF deviations did not exceed the tolerance limits of ± 0.5 % according to IEC 60584-1 reference tables.

Figure 4 shows the changes in thermocouples readings at the temperature of 2000 °C for 50 h. It can be seen that all type A thermocouples and two of type C (C2, C3) decreased by (15–30) °C for 28 h (average drift 0.78 °C per hour), then their readings stabilized until the end of the test. Thermocouples C1 and C4 maintained their stability until the end of the tests, and thermocouple C5 had small positive temperature drift. All thermocouples remained operational to the end of the test, and the drift of the readings of 6 thermocouples remained within 1 % tolerance limit.

To test thermocouple stability at 2200 °C, new thermocouples of types A and C were used (see Table 1). All thermocouples corresponded to the tolerance limits of ± 0.5 % within the range (600–1700) °C. At the beginning of the test, just after the temperature reached 2200 °C thermocouple readings immediately showed some signal shunting (reduction) with negative deviation from the set temperature on 5 °C to 15 °C. But then during 2 h thermocouples behaved differently: C1 and A1 increased

Table 1 Summary the experimental tests made and description of thermocouple specimens

Test	Test temperature (°C)	Specimen description						
		Type	Quantity (pcs.)	Wire diam. (mm)	Insulation type, diameters/length (mm)	Sheath D × s[a] (mm)	Immersion length (mm)	Initial calibration range/tolerance (°C) / %
Stability test	2000	A	5	0.5	HfO_2, 4 × (2 × 1) / 300	–	400	(1000–1600) / ± 0.5
		C	5	0.5	Al_2O_3, 4 × (2 × 0.8) /100			
Stability test	2200	A	5	0.5	HfO_2, 4 × (2 × 1) / 300	–	400	(600–1700)/ ± 0.5
		C	3	0.5	Al_2O_3, 4 × (2 × 0.8) /100			
Probe test	(1600–2500)	A	1	0.5	HfO_2, 4 × (2 × 1) / 300 Al_2O_3, 4 × (2 × 0.8) /100	Mo tube 6.3 × 0.3	400	(800–1600) / ± 0.5
Probe test	(1600–2500)	A	1	0.5	MgO, 6 × (2 × 0.7) / 400	Mo tube 10 × 1	400	(800–1700)/ ± 0.5
Calibration with ref. pyrometer	(1500–1700)	A	1	0.5	HfO_2, 4 × (2 × 1) / 300 Al_2O_3, 4 × (2 × 0.8) /100	–	400	(800–1700) / ± 0.5
Calibration bare wires	(1200–2500)[b]	A	1	0.5	Bare wires	–	400	(1200–1600) / ± 0.5

[a]Sheath outer diameter and wall thickness

[b]There were made 5 consequent tests including one test up to 2600 °C

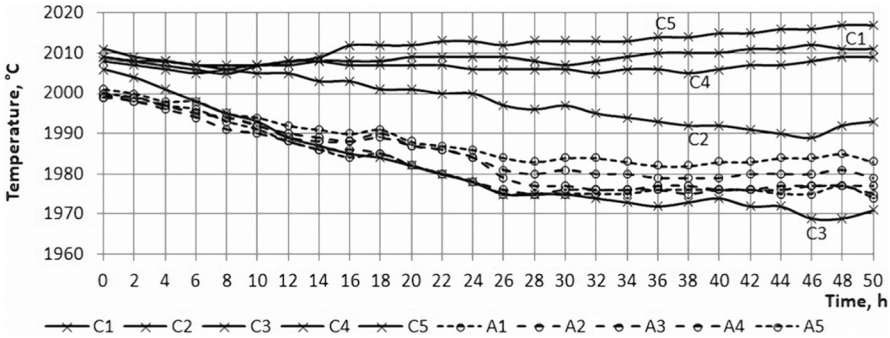


Fig. 4 Change in readings of W–Re thermocouples during stability test for 50 h at 2000 °C (thermocouples A1…A5—of type A; C1,…,C5—of type C)

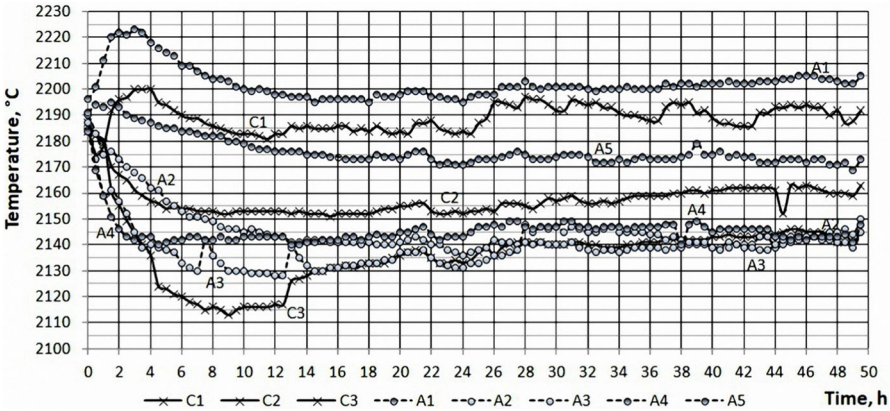


Fig. 5 Change in readings of W–Re thermocouples while annealing at 2200 °C (thermocouples A1…A5—of type A; C1,…,C3—of type C)

their readings up to 25 °C and began to decrease, A5 thermocouple increased readings by 5 °C and began to decrease, the rest thermocouples continuously reduced their readings by values from 40 °C to 60 °C (Fig. 5) for 14 h and then were stable. Until the end of the test, only two thermocouples practically retained their readings relative to the initial values, one of type C and one of type A (C1 and A1 in Fig. 5).

Despite of sufficiently long annealing (49 h) at ultra-high temperature, the thermocouples showed surprisingly similar temperature values during cooling to the initial calibration temperature of 1700 °C. The readings of all thermocouples deviated within (4–8) °C from their initial calibration values. All of them measured the actual temperature in the furnace with error not exceeding ± 0.5 % of 1700 °C.

Signal shunting effect at 2200 °C leads to the fast thermocouple drift which stabilized in (12–14) h. When temperature decreased below 2000 °C shunting effect disappeared and thermocouples showed readings close to initial calibration values.

Fig. 6 A single probe in protective molybdenum tube

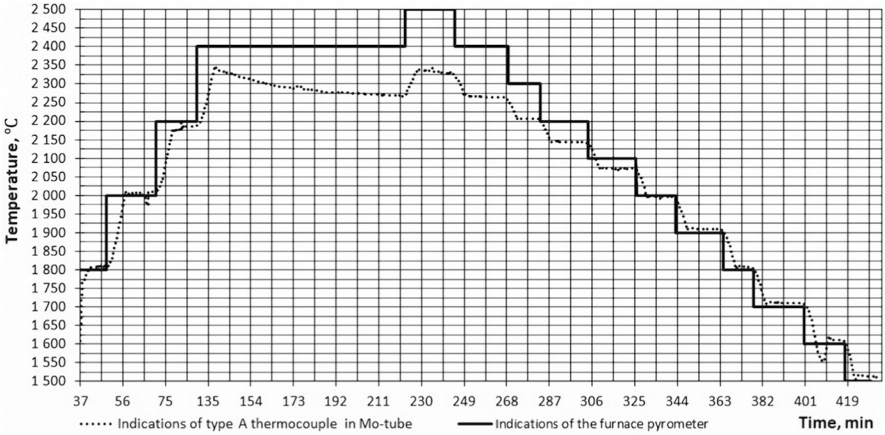


Fig. 7 Change in type A probe readings during stepwise heating up to 2500 °C and cooling down to 1500 °C in comparison with furnace temperature controlled by feedback pyrometer

3.2 Specimen Testing in Protective Tube

Testing the sensor having protective tube at extreme temperatures was of great interest from the lifetime point of view and measurements accuracy. The test was made in argon inert atmosphere in presence of graphite vapor emitting by heater. In these conditions active interaction of structural materials of the sensor might be possible [5].

To check the probe operability at the upper temperature limit, complete type A thermocouple was placed in a molybdenum protective tube, which was immersed directly into the cavity of radiation block (see Fig. 1) inside the furnace working space.

The furnace temperature was controlled by the furnace feedback pyrometer. The probe thermocouple had known calibration in the temperature range (800–1600) °C and it was put in the protective tube of 6.3 mm outer diameter and wall thickness of 0.3 mm (Table 1; Fig. 6). Two-channel hafnia insulators of 4 mm diameter were used. The channels diameter was of 1 mm and thermocouple wires of 0.5 mm diameter. Thus, the maximum possible gaps between the elements were provided inside the probe to reduce shunting effect of thermocouple signal at high temperature. To ensure an inert atmosphere, internal space of the sensor was filled with argon and sealed.

The furnace was heated in steps by 200 °C during heating and 100 °C during cooling (Fig. 7). Each step took (10–12) min and (10–15) min for temperature stabilizing. At the levels of 1800 °C and 2000° C positive shift of the thermocouple

readings by (10–11) °C from pyrometer readings was recorded. This was consistent with initial calibration data at 1600 °C (+7.1 °C).

When heated from 2000 °C to 2200 °C the signal shunting phenomenon was first observed. Thermocouple readings began to deviate in negative direction from pyrometer readings by (13–15) °C, but they shifted and were at the same time quite stable. Temperature increase to 2400 °C immediately revealed significant decrease in thermocouple readings to minus 55 °C relative to pyrometer indications. Moreover, permanent negative drift of thermocouple readings was observed, ranging from minus 5.0 °C for the first minute to minus 1.5 °C/min after 10 min annealing. After 1.5 h of annealing negative drift rate of the thermocouple was 0.4 °C/min. The thermocouple readings dropped to the value of 2268 °C, or minus 132 °C relative to the furnace temperature of 2400 °C. Thus, the initial shunting effect minus 55 °C added another minus 77 °C during 1.5 h of annealing at 2400 °C. After further furnace heating to 2500 °C thermocouple readings reached the value only 2338 °C having total shunting effect of minus 162 °C. However, the thermocouple remained functional and restored its readings when temperature was dropped to 2000 °C.

Better results were got with type A thermocouple insulated by MgO tubes of 6×(2×0.7) mm placed into molybdenum tube of 10×1 mm diameter (see Table 1). It was heated to 2400 °C and thermocouple indications were meaningful up to 2300 °C. They had negative drift of 13 °C but it was within 1 % tolerance limit. The probe remained to be a measuring instrument at 2300 °C. When heating and annealing at 2400 °C we saw signal shunting to 2358 °C and then 11-degrees negative drift from the initial reading for 0.5 h. Indications fully restored at 1900 °C.

Thus, the results of experiments at the upper temperature limit showed that the probe with type A thermocouple is operable up to the temperature of 2500 °C, outlook of the thermocouple and protective tube after the tests was satisfactory. Metallic coating was visible on the insulators because the temperatures (2400–2500) °C are quite high for molybdenum protective tube ($T_{melting}$ = 2620 °C). Molybdenum turned out the best material for protective tubes of temperature sensors. We have checked also niobium and tantalum tubes but they had active chemical reaction with other parts of thermocouple assembly at high temperatures under graphite vapor presence. Tungsten tubes of small diameter are rare and very expensive. However, available insulation materials do not allow the long-term use of W–Re thermocouples at temperatures of 2200 °C and above. Shunting and drift of thermocouple signal leads to its readings move beyond 1 % tolerance limit according to IEC 60584-1:2013. The calibrated temperature measuring instrument turns into temperature indicator with the accuracy of no better than (2–6) %. In addition, high-temperature annealing leads to deformation and shrinkage of insulating ceramics. For example, hafnia tubes shrink on 10 mm per 300 mm of the total length while exposing to (2000–2200) °C.

It should be noted that the use of bare-wire thermoelements in high-temperature part of a sensor can reduce the signal shunting effect to a minimum.

3.3 Calibration of W–Re Thermocouples Against Reference Radiation Pyrometer

Calibration of thermocouples was carried out according to the scheme shown in Fig. 1. Thermocouples were assembled around the central carrier tube placed in protective tube and then immersed to cavity of the furnace radiation block,

Sighting index of reference pyrometer should be large enough to register total radiation flux from the bottom plug of central tungsten tube having length of 500 mm and internal diameter of 8 mm. It should be at least 100:1, so that only area of reflecting plug of the tube gets into the field of view of the pyrometer. Surface of reflecting plug was profiled to dissipate radiation inside the tube. Having uniform temperature at the length of about 50 mm along the axis, we obtain isothermal cavity with the height of more than six internal diameters. Emissivity coefficient is quite large and weakly depends on spectral characteristics of tungsten. Calculation of optical characteristics of the pyrometer for this research is given in [16].

During calibration, each thermocouple was connected to its own millivoltmeter-temperature recorder with autonomous power supply (batteries set). All measuring instruments had built-in temperature compensator for cold junctions of thermocouples and were pre-calibrated for compliance with reference tables of types A and C thermocouples with maximum deviations from nominal values not exceeding 1 K in the whole temperature range of measurements.

Thermocouples were made (see Table 1) of wire coils pre-calibrated in the temperature range (800–1700) °C against a reference type B thermocouple. These data served as reference points for subsequent thermocouple calibration against reference pyrometer. Convergence of two calibrations in the range (1500–1700) °C confirms reliability of calibration results at higher temperatures, where pyrometer readings well obey the Planck radiation law.

Figure 8 shows summary graphical representation of two calibrations for the same pair of W–Re wires in the form of thermal EMF deviations from the nominal values, expressed in degrees, over whole operating temperature range. It can be seen

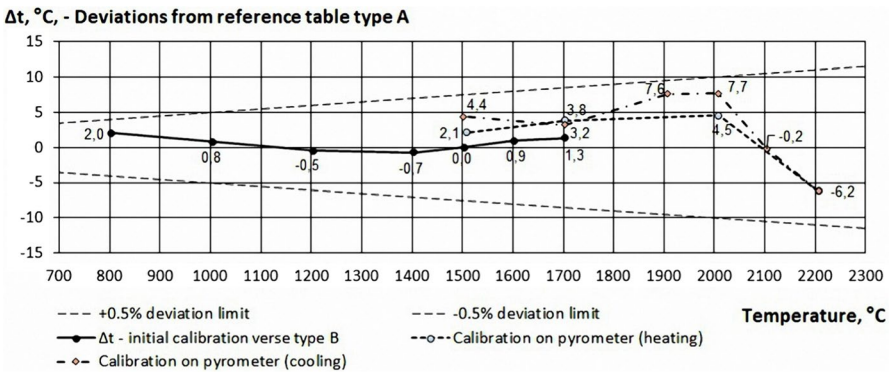
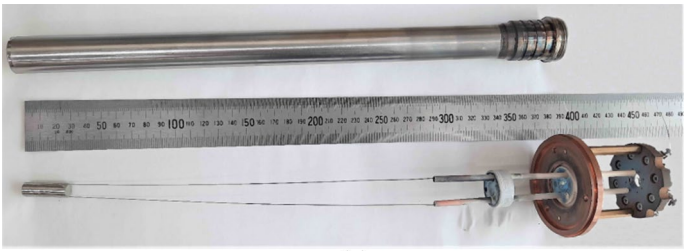
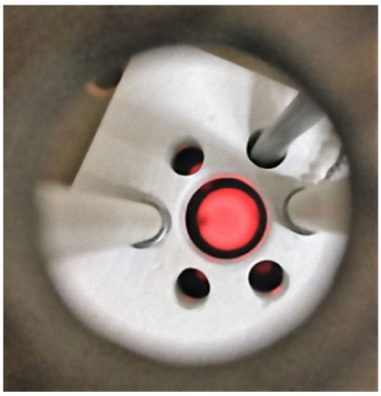


Fig. 8 Calibration of type A thermocouple in the operating temperature range against the readings of reference type B thermocouple (800–1700 °C) and relative to the readings of radiation pyrometer (1500–2200 °C)



(a)



(b)

Fig. 9 Type A bare-wire thermocouple assembly and massive hot junction (a) centered in working cavity of protective tungsten tube (b)

that in the range (1500–1700) °C the discrepancy between two calibrations before and after annealing at 2200 °C consists of (2.1–4.4) °C.

A fiber-optic pyrometer with 100:1 sighting index was used as the reference instrument. Because of non-ideal radiation from the cavity of central tube radiation coefficient of the pyrometer established as 0.97. Calibration curves clearly show the signal shunting effect above 2000 °C, but thermocouple remained within the tolerance limit of 0.5 %.

To eliminate shunting effect while calibrating W–Re thermocouple to the upper limit of temperature measurements, special sensor was made (Fig. 9a). Working junction was made in the form of tungsten cylinder of 10 mm diameter and 30 mm height. The cylinder was suspended on W-5 %Re and W-20 %Re wires of 0.5 mm diameter. Wires were passed through side grooves on the cylinder surface. Thermoelements were insulated with alumina tubes at cold upper part of the sensor and were fixed to terminal block.

In this case, working space temperature of the furnace was controlled both by furnace feedback pyrometer and by reference pyrometer focused on the upper end of tungsten cylinder (working junction) placed along the central axis in the uniform temperature zone (Fig. 9b). Radiation coefficient of reference pyrometer was

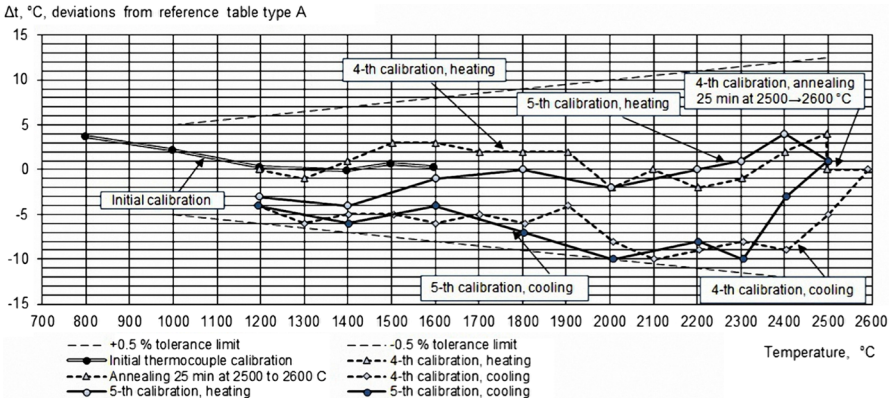


Fig. 10 Calibration curves of type A bare-wire thermocouple in the temperature range (1200–2500) °C

adjusted to the blackness degree of 1.0. Working cavity of outer protective tube (internal diameter 21 mm) for thermocouple assembly had better emissivity property than central carrier tube of 8 mm diameter.

During calibration reference points of initial thermocouple calibration in the range (1200–1600) °C were used. Five calibrations of type A thermocouple in the range (1200–2500) °C and long-term annealing at 2400 °C and 2500 °C (up to 60 min) were carried out. One run was also carried up to 2600 °C, beyond the measuring temperature range. Thermocouple EMF was measured 34.36 mV at 2600 °C with medium differential sensitivity ~ 7.2 μV·K within the range (2500–2600) °C. The thermocouple remained fully functional after testing and was within the ± 0.5 % tolerance limit (Fig. 10). Negative drift (in degrees) of the thermocouple deviation relative to the initial calibration did not exceed 6 °C.

Thus, the UKT-2500 installation made it possible to calibrate W–Re thermocouples in the entire range of measuring temperatures by comparison with reference pyrometer readings.

4 Conclusion

Presented results of the research showed the possibility to calibrate a single or several W–Re thermocouples simultaneously in the range of working temperatures, which is important in their serial production. Various calibration methods can be realized with the developed installation: method of comparison with a reference thermocouple, comparison with radiation pyrometer readings, calibration at reference fixed-points of Me–C type. W–Re thermocouple calibration is reliable up to 2000 °C when thermocouple wires are insulated with hafnia or magnesia ceramic tubes. Expanded uncertainty of measurements at this temperature evaluated as 80.4 μV or 7.7 K. In the range (2000–2200) °C increasing shunting effect of thermocouple signals was observed. The authors could realize calibration of type A

bare-wire thermocouple at any operating temperature, including the upper limit of measurements 2500 °C.

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Declarations

Competing interests Authors declare that they have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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