

POSTUPAK KALIBRACIJE I UTICAJI KOJI SE UZIMAJU U OBZIR TOKOM KALIBRACIJE KONTAKTNIH TERMOMETARA ZA MJERENJE TEMPERATURE ČVRSTE POVRŠINE

CALIBRATION PROCESS AND IMPACTS TAKEN INTO ACCOUNT DURING THE CALIBRATION OF CONTACT THERMOMETERS FOR TEMPERATURE MEASUREMENT OF SOLID SURFACE

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Ključne riječi:
*Kalibracija, kontaktne
termometri, mjerena
nesigurnost*

Keywords:
calibration, contact
thermometers,
measurement uncertainty

Paper received:
21.09.2015

Paper accepted:
04.11.2015.

Originalan naučni rad

REZIME

Na prototipu/etalonu – aparatura za kalibraciju kontaktnih termometara na čvrstoj površini (u nastavku teksta prototip), izvršena su mjerenja odnosno kalibracija kontaktog termometra. Kako bi dobijeni rezultat kalibracije bio potpun izvršena je procjena mjerne nesigurnosti.

Iskorištena je mogućnost variranja parametra uticaja ambijentne temperature tik iznad referentne površine. Ovaj parametar je direktno proistekao iz konstrukcije samog protitpa.

Original scientific paper

SUMMARY

Measurements, calibrations of contact thermometer have been conducted on prototype/standard – apparatus for calibration of contact thermometers on solid surface (in following text just prototype). In order to make the calibration obtained result whole an estimation of measurement uncertainty is done.

The possibility to vary parameter of influence of ambient temperature just above the reference surface is used. This parameter is directly derived from the construction of the prototype.

1. UVOD

Kako bi bili sigurni u rezultate mjerenja kontaktnim termometrom svako mjerilo odnosno senzor mora biti provjeren, kalibriran. Kalibracija je operacija koja, pod određenim uvjetima, u prvom koraku, određuje odnos između vrijednosti veličine sa mjernom nesigurnošću od etalona mjerjenja i odgovarajućih pokazivanja sa pridruženim mernim nesigurnostima, a u drugom koraku, koristi ovu informaciju da uspostaviti odnos za dobijanje mjerne rezultata iz očitanja. [1] Kontaktne termometre za mjerjenja na čvrstoj površini su predmet kalibracije na prototipu i imaju svoj udio u doprinosima pri procjeni mjerne nesigurnosti.

1. INTRODUCTION

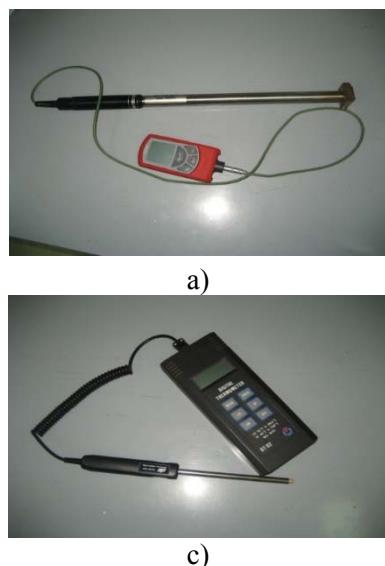
To be sure in measurement results of contact thermometer every measure or sensor must be checked, calibrated. Calibration is the operation that, under certain conditions, in a first step, define the relationship between the value of the size of the uncertainty of measurement standards and corresponding indications with associated measurement uncertainty, and in the second step, uses this information to establish a relation for obtaining a measurement result of the reading. [1]

Contact thermometers for measuring the solid surface are subject to calibration on a prototype and have their share of contributions to the assessment of measurement uncertainty.

Naime, široka je primjena kontaktnih termometara u prehrambenoj industriji, kulinarstvu, te raznim granama industrije, gdje se javlja potreba za mjerjenje temperature čvrste površine. Na primjer premazi na bazi recijskih smola se ne smiju primjenjivati na temperaturama ispod tačke rosišta ili na temperaturi ispod 5°C te se u te svrhe koristi kontaktni termometar kao i u auto industriji i drugim lakirerskim granama, gdje se premazi odnosno slojevi nanose tek nakon provjere temperature koristeći kontaktne termometre. Isti također imaju primjenu kod praćenja temperature toplovnih vodova, građevinarstvu i u mnoge druge svrhe.

2. POSTUPAK KALIBRACIJE KONTAKTNIH TERMOMETARA ZA MJERENJE TEMPERATURE ČVRSTE POVRŠINE I KORIŠTENA OPREMA

Postoje različite izvedbe kontaktnih termometara za mjerjenja na čvrstoj površini čiji senzori su obično termoelementi ili otporni termometri. Na Slici 1. su dati samo neki primjeri izvedbi ove vrste kontaktnih termometara.



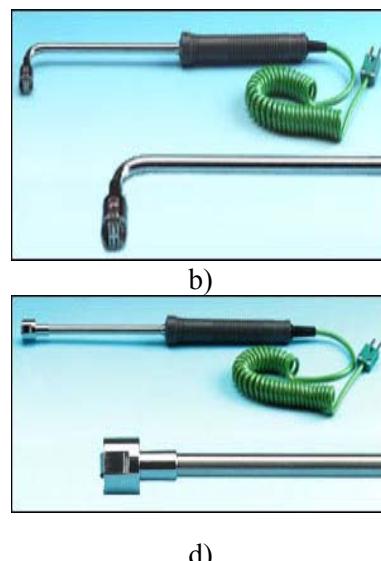
*Slika 1. Kontaktni termometri za mjerjenja temperature na čvrstoj površini
Figure 1. Contact thermometers for measuring temperature at solid surface*

Uporedna metoda kalibracije senzora temperature je metoda, gdje se do rezultata kalibracije dolazi na bazi uporednog očitavanja etalona poznatih karakteristika i mjerila koje se podvrgava kalibraciji i to na temperturnim tačkama ostvarenim uz pomoć korištenja odgovorajuće aparature.

Namelly, there is wide application of contact thermometers in the food industry, culinary, and various industries, where there is a need to measure the temperature of the solid surface. For example coatings based secretion resin should not be used at temperatures below the dew point or at a temperature below 5°C. So contact thermometers are used for this purpose as well as in the auto industry and other branches of the paint, where the coatings or layers are applied only after checking the temperature using a contact thermometer. The same also have application in the monitoring of temperature heat pipes, construction and many other purposes.

2. THE METHOD OF CALIBRATION OF CONTACT THERMOMETERS FOR TEMPERATURE MEASUREMENT OF SOLID SURFACE AND USED EQUIPMENT

There are different versions of contact thermometers for measuring temperarture of solid surface whose sensors are typically thermocouples or resistance thermometers. The Figure 1 shows only some exemplars of these types of contact thermometers.



The comparison method of calibration of temperature sensor is a method where the calibration results are obtained on the basis of comparative readings of standard of known characteristics and measure that is calibrated at certain temperature points achieved by using appropriate apparatus.

Očitana razlika predstavlja odstupanje kalibrišanog mjerila od vrijednosti zadate kalibracione tačke. Jedan od načina mjerjenja temperature na čvrstoj površini je mjerjenje kontaktnim termometrima. Mjerjenje temperature na ovaj način je proisteklo iz mnogih aspekata života i rada, te otud i potreba za "pravilnom" provjerom odnosno kalibracijom te vrste termometara.

Većina termometara pravljena tako da se koriste, a i kalibrišu uporednom metodom odnosno da se uranjaju u mjerni medij, bez da ambijentni uvjeti imaju značajan utjecaj na konačan rezultat.

Ali kada je riječ o kontaktnim senzorima za mjerjenje temperature (čvrste) površine i kalibraciji istih oni u potpunosti odstupaju od ovog pravila. Oni su koncipirani za direktnu primjenu odnosno mjerjenje na čvrstoj površini. [2, 3].

Slijedom navedenog nekoliko nacionalnih metroloških laboratorijskih je razvilo uređaje koji generišu temperaturu površine pod uvjetima koji najviše nalikuju onima koji se susreću tokom uobičajenog korištenja površinskih senzora. [4]. A slijedeći primjer prototip ove vrste aparature je razvijen i na Metalurškom institutu "Kemal Kapetanović" Zenica.

Kontaktni termometri se općenito kalibrišu uz korištenje kontrolirane temperature vruće ploče. Na ovakovom uređaju referentna temperatura je ona na gornjoj površini metalnog tijela, a ista se određuje linearnom ekstrapolacijom iz očitanja kalibriranih senzora (sondi) koji su uvučeni u tijelo na različitim dubinama odnosno udaljenostima od referentne površine. Stvarna temperatura referentne površine u mnogome zavisi od interakcije senzora na površinu. [5, 6] Princip kalibriranja senzora za mjerjenja na površini je poređenje standardne temperature površine (dobijenom ekstrapoliranjem) sa temperaturom senzora određenom kad se senzor za mjerjenje na površini direktno prisloni na jedan od materijala (referentnih površina).

Prema Michaelsky-om [2] metod ekstrapoliranja predstavlja jedan od najpreciznijih načina određivanja temperature površine čvrstih tijela, a bazira se na principima datim na slici 2.

Za određivanje temperature referentnih tijela koja su deblja, a koja se mogu posmatrati kao polu-beskonačna tijela, također se može koristiti metod Yarisheva i Minina (1969) koji se pokazao kao veoma precizan. Ovaj metod se zasniva na mjerjenju temperature q_1 i q_2 sa dva senzora, na određenim rastojanjima x_1 i x_2 od referentne površine, pri čemu se temperatura površine računa iz izraza:

The difference that is read out represents the deviation of calibrated measure from the value of set calibration point. One way to measure the temperature of the solid surface is a measurement by using contact thermometers. Temperature measurement in this way is derived from the many aspects of life and work, and hence the need for a „proper“ checking and calibration of this type of thermometer. Most thermometers are created so that it is used and calibrated by comparison method meaning to be immersed in the measuring medium, where ambient conditions have no significant impact on the final score.

But when it comes to contact sensors for measuring temperature of (solid) surface and calibrating them they completely deviate from this rule. They are designed for direct application or measurement on a solid surface. [2, 3].

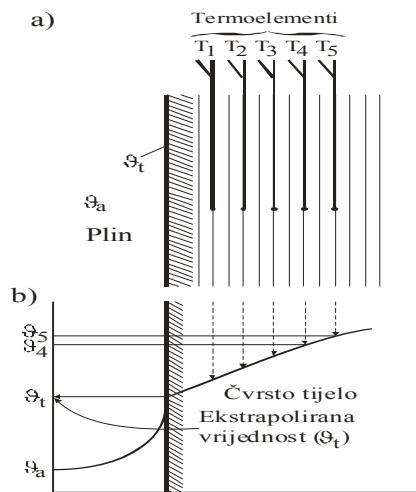
Consequently, several national metrology laboratories have developed devices that generate a surface temperature under conditions that most closely resemble those encountered during normal use of the surface sensors. [4]. And following example of the prototype of this kind of apparatus has been developed and the Metallurgical Institute "Kemal Kapetanovic" Zenica.

Contact thermometers are generally calibrated using temperature-controlled hot plate. For such a device reference temperature it is on the upper surface of the metal body, and it is determined by linear extrapolation from the readings of calibrated sensors (probes) that are pulled into the body at different depths and distances from the reference surface. The actual temperature of the reference surface depends largely on the interaction of the sensor to the surface. [5, 6]

The principle of calibration of sensors for measuring the surface is comparison of standard surface temperature (obtained by extrapolating) with temperature from sensor specified when the sensor for measuring the surface is directly pressed on one of the materials (the reference surface).

According to Michaelsky [2] the extrapolation method represents one of the most precise ways to determine temperature of solid body and is based on principles shown at figure 2.

To determine the temperature of the reference bodies that are thicker and which can be seen as a semi-infinite body, can also be used method Yarisheva and Min's (1969) which proved to be very precise. This method is based on measuring the temperature of q_1 and q_2 from the two sensors, the specified distance x_1 and x_2 of the reference surface, wherein the surface temperature is calculated according the expression:



Slika 2. Shematski prikaz metoda mjerjenja temperature ekstrapoliranjem
Figure 2. Schematic representation of the method of temperature measurement by extrapolating

$$\vartheta_t(t) = \vartheta_1(t) \left[\frac{x_2}{x_2 - x_1} - \frac{x_2}{x_2 - x_1} \sqrt{\frac{\vartheta_2(t)}{\vartheta_1(t)}} \right]^3 \quad (1)$$

Sa malim područjem variranja temperature i malim temperaturnim razlikama u referentnom tijelu, kao što su ploče konačno male debljine, moguće je obezbijediti konstantnu ili približno konstantnu termičku provodnost λ_b , što znači da je pad temperature u tijelu vrlo blizak linearom. U ovom slučaju se radi o veoma jednostavnoj linearnoj ekstrapolaciji, zasnovanoj na dvije mjerne vrijednosti što se može izraziti slijedećom jednadžbom:

$$\vartheta_t(t) = \frac{\vartheta_1(t)x_2 - \vartheta_2(t)x_1}{x_2 - x_1} \quad (2)$$

Metoda ekstrapolacije se u principu koristi za mjerjenje temperature referentnih površina gdje su kontrolirani uvjeti i obezbjedeno stacionarno stanje sistema.

Obično se koriste tanki termolementi koji su postavljeni uzduž izotermi unutar čvrstog tijela. Samo se takvi termolementi sa mjernim krajevima izoliranim vratostalnim izolacionim materijalima koriste u metalima i poluprovodnicima. Metoda ekstrapoliranja je zasnovana na pokazivanju temperature svakog pojedinog termolementa te se tako može odrediti temperatura površine bez da se deformiše temperaturno polje odnosno naruši originalna raspodjela temperature površine. [2, 7] Glavni izvori greški kod ekstrapolacione metode su vezani za nehomogenost i anizotropiju materijala od kojeg je izrađeno referentno tijelo i zbog deformacije temperaturnog polja do kojeg dolazi uvođenjem senzora unutar referentnog tijela.

With a little variation of temperature and low temperature differences in the reference body, such as the board of ultimately small thickness, it is possible to provide a constant or nearly constant thermal conductivity λ_b , which means that the temperature fall in body very close to linear. In this case it is a very simple linear extrapolation, based on two measured values that can be expressed in the following equation:

$$\vartheta_t(t) = \frac{\vartheta_1(t)x_2 - \vartheta_2(t)x_1}{x_2 - x_1} \quad (2)$$

Extrapolation method is generally used to measure the temperature of the reference surface where conditions are controlled and secured stationary state.

Commonly are used thin thermocouples which are placed along the isotherms within a solid base. Only such thermocouples with measuring ends isolated refractory insulation materials used in metals and semiconductors. The method of extrapolating is based on the temperatures of each thermo' couples and thus can determine the surface temperature without deforming temperature field and distort the original distribution of the surface temperature. [2, 7]. The main sources of errors in extrapolation methods are related to the inhomogeneity and anisotropy of the material from which a reference body is made and due to the deformation of temperature field that occurs by introducing the sensor within the reference body.

Za otklanjanje ili minimziranje ovih izvora greški preporučuje se primjena termoelemenata koji su što je moguće tanji, te njihovo uvodenje u tijelo uzduž izotermi.

2.1. Prototip – aparatura za kalibraciju kontaktnih senzora za mjerjenje temperature čvrste površine

Na slici 3. dat je izgled prototipa i referentnog tijela/ ploče i drugi podaci vezani za iste.

Sa prototipom - aparaturom za kalibraciju kontaktnih termometara se nastojalo postići da ima temperaturni omjer: od ambijentne do 600 °C. To je moguće ostvariti primjenom izmjenjive referentne ploče. Jedna od bakra za opseg od ambijentne do cca 250 °C i druga od „procrona“ – Č.4171 po JUS-u za opseg temperature do 600 °C. Na slici 4. je predstavljena referentna površina izrađena od čelika.



Slika 3. Prototip aparature za Figure 3.

U radu je vršeno variranje i mjerjenje parametra koji se ne može zanemariti, a koji je proistekao iz karakteristika izvedbe prototipa. Parametar vezan za uticaj na ambijentnu temperaturu tik iznad površine, a nastao kao posljedica broja, rasporeda i pozicije grijачa u prototipu.

2.2. Opis prototipa

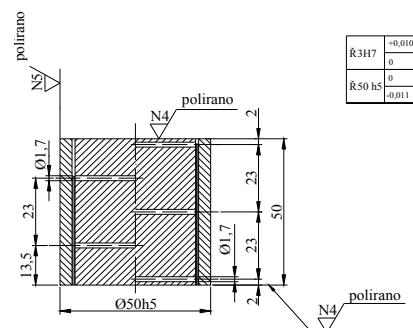
Kalibrirani termoelementi tipa K, sa slike 5. su smješteni na različitim udaljenostima, paralelno sa površinom referentnog tijela/ ploče. Isti termoelementi su prikopčani na digitalni termometar sa četiri kanala Chub-E4 (Slika 6), u svrhu praćenja vrijednosti temperature unutar referentnog tijela, te korištenja tih podataka za ekstrapoliranje temperature referentne površine.

To eliminate or minimize these sources of errors is recommended to use a thermocouple which is as thin as possible, and their introduction into the body along the isotherms.

2.1. Prototype - apparatus for calibrating contact sensors for measuring the temperature of the solid surface

Figure 3 gives an appearance of a prototype and reference bodies / boards and other data related to the same.

With the prototype - apparatus for calibrating contact thermometers has sought to achieve a ratio of temperature: from ambient to 600 ° C. This can be achieved by using removable reference board. One of the copper for a range of ambient to about 250 ° C and the other of "procron" - Č.4171 by JUS for the temperature range up to 600 ° C. Figure 4 presents the reference surface made of steel.



Slika 4. Referentna ploča/blok (tijelo izrađeno od čelika) Figure 4. The reference plate / block (body made of steel)

The research focused on measuring the variation of the parameter that cannot be ignored, and that came out of the performance characteristics of the prototype. Parameters related to the impact on the ambient temperature just above the surface, and came as result of the number, arrangement and position of the heater in the prototype.

2.2. Description of the prototype

Calibrated thermocouples type K, presented on Figure 5 are located at different distances parallel to the surface of the reference body / board. The same thermocouples are connected to a digital thermometer with four channels Chub-E4 (Figure 6), in order to monitor the value of the temperature inside the reference body, and use this data to extrapolate the temperature of the reference surface.

Ovakvo pozicioniranje senzora karakteristično i kod drugih aparatura koje su ranije razvijene, s tim da nisu na svim aparaturama korišteni termoelementi tip K kao senzori.

This positioning of the sensors is characteristic in the other apparatuses that have previously been developed. But, type K thermocouples as sensors were not used at all the apparatus.



Slika 5. Termoelmenti, grijaci i regulator koji su u sastavu aparature
Figure 5. Thermocouples, heaters and regulator that are part of the apparatus



Slika 6. Digitalni termometar Chub-E4 na koji su prikopčani termoelementi za praćenje temperature unutar referentnog tijela za ekstrapoliranje
Figure 6. Digital thermometer Chub-E4 to which the thermocouples are connected to monitor the temperature within the reference body and to extrapolate

Figure 6. Digital thermometer Chub-E4 to which the thermocouples are connected to monitor the temperature within the reference body and to extrapolate



Slika 7. Slika tiristorskih sklopki za regulaciju temperaturna grijaca
Figure 7. Thyristor switches to control temperature heaters

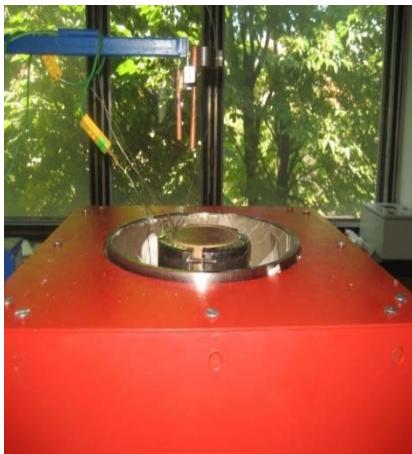
Termoelemenati tip K (prikazani na slici 5), su također korišteni i za regulaciju temperatura grijaca i uvezani sa regulatorom Imago 500 (slika 5) i tiristorskim sklopkama proizvođača JUMO, tip B 70.9040.0 (slika 7.). Sve zajedno čini jedan sistem za reguliranje temperature referentnog tijela.

Svi termoelementi i digitalni termometar su prethodno kalibrirani u svrhu provjere i sljedivosti istih.

Thermocouple type K (shown in Figure 5), were also used for regulating the temperature of the heater and connectd with other regulator Imago 500 (Figure 5) and thyristor switches manufacturer JUMO, type B 70.9040.0 (Figure 7). All together makes a system to regulate the temperature of the reference body.

All thermocouples and a digital thermometer are pre-calibrated for the purpose of verification and traceability of the same.

Ispod referentnog tijela je jedan grijач u keramici, a dva u obliku prstena (slika 5.) su oko i iznad ili ispod i oko referentnog tijela/ ploče. Jedan položaj referentne ploče je kada se ista nalazi u „gornjem“ položaju i tada je praktično referentna ploča u visini (poravnata) sa gornjim obodom gornjeg (prestenastog) grijaca koji u tom slučaju grije referentnu ploču okolo. (Slika 8).



Slika 8. Gornji položaj referentnog tijela/ ploče
Figure 8. Upper position of reference of body/
 plate

Drugi položaj je kada je referentna ploča u „donjem“ položaju i tada donji (prstenasti, a srednji od tri) grijac grije referentnu ploču okolo, a gornji grijac je u višem položaju u odnosu na referentnu ploču i na taj način ima uticaja na ambijentnu temperaturu tik iznad same površine referentne ploče. (slika 9).

Ovo je značajan podatak jer je ovo novina na prototipu odnosno jedno od unapređenja ove aparature. Ovaj podatak je važan i utoliko jer će isti biti iskorišten za poređenje rezultata dobijenih u jednom i u drugom položaju aparature na istim temperaturnim kalibracionim tačkama.

2.3. Postupak kalibracije kontaktnih termometara

2.3.1. Metodologija rada i koraci izvođenja kalibracije kontaktnog termometra

Ne postoji definirana metoda odnosno standard za kalibraciju kontaktnih termometara na prototipu odnosno aparaturi ove vrste. Moguće je generalno dati ideju kako sortirati operacije koje se izvode tokom kalibracije.

Below the reference body is a heater in ceramics, and two ring (Figure 5) around and above or below and around the reference body / board.

One position of the reference board is when the same is in the "top" position and then practically the reference board is in height (aligned) with the upper rim of the upper (ring) heater, which in this case heated the reference sheet around. (Figure 8).



Slika 9. Donji položaj referentnog tijela/ ploče
Figure 9. Lower position of reference of body/
 plate

The second situation is when the reference plate in the "lower" position and then the lower (the ring, and the mean of three) heater heats the reference plate around, and the upper heater is in a higher position relative to the reference plate and in this way influences the ambient temperature just above the surface of the reference board. (Figure 9). This is an important fact because this is a novelty on the prototype that one of the improvements of the apparatus. This information is important in so far as they will be used to compare the results obtained in one and in the second position of the apparatus at the same temperature calibration points.

2.3. Contact thermoemeters calibration procedure

2.3.1. Methodology and steps performing calibration of contact thermometer

There is no defined method or norm for calibration of contact thermometers on a prototype or apparatus of this type. It is possible to give a general idea of how to sort operations performed during calibration.

Iz navedenih razloga veliki dio procedure izvođenja kalibracije kontaktnog termometra je preuzet iz Projekta Termometrija 635, a dijelom po uzoru na bilateralno poređenje između BNM-LNE (Francuska) i OMH (Mađarska).

Procedura za kalibraciju:

1. Uključuje prvo i konačno, određivanje površinske temperature ekstrapoliranjem prije primjene senzora ($t_{p-prije}$) na određenoj kalibracionoj tački.

Temperature površine mjerene ekstrapoliranjem bi trebalo da ostanu unutar $\pm 2^{\circ}\text{C}$ od nominalne temperature, a u svrhu da se izbjegne korekcija koja nastaje uslijed razlike između nominalne tačke i temperature površine.

2. Slijedeći korak je prislanjanje kontaktnog termometra na površinu referentnog bloka u svrhu mjerjenja i dobijanja podataka očitanih sa termometra.

Kontaktni termometar se potom primijeni ručno. Po uzoru na projekat Termometrija 635[4] i bilateralno poređenje BNM-LNE i OMH [9] trebalo bi da su zabilježena tri mjerjenja izvedena na kalibracionoj tački, a srednja vrijednost bi definirala temperaturu (t_k). Ili se može vršiti više mjerjenja: „Procedura ipak može biti prilagođena imajući u vidu da neki senzori zahtjevaju više mjerjenja; mjerjenja sa površinskim senzorom ponavlja operater dok se ne utvrdi da je mjerena vrijednost stabilna“. [8]

3. Nakon uklanjanja kontaktnog termometra (senzora), površinska temperatura se još jednom određuje ekstrapoliranjem ($t_{p-poslje}$). Prosječna temperatura površine određena ekstrapoliranjem definira referentnu temperaturu (t_p), što je i osnovna vrijednost između ($t_{p-prije}$) i ($t_{p-poslje}$).
4. Dakle mjerena temperatura referentne površine i predmeta kalibracije – kontaktnog termometra (senzora) se vrše kako je opisano i to jedan ciklus kada je referentno tijelo u „donjem“ položaju (Slika 8.), a potom mjerjenje na istoj kalibracionoj tački kada je referentna površina u „gornjem“ položaju (Slika 9.).

Na taj način, kada je referentna površina u „donjem“ položaju, se temperatura ambijenta tik iznad referentne površine praktično zagrijava na zadatu temperaturu, a i kontaktni termometar koji se postavi tik iznad referentne površine se na taj način „predgrijava“ te nakon prislanjanja istog na referentnu ploču „oduzima“ manje toplote sa referentne ploče.

For these reasons, a large part of the procedure performing calibration of contact thermometer is taken from Project Thermometry 635, and partly modeled on a bilateral comparison between BNM-LNE (France) and the OMH (Hungary).

Calibration procedure:

1. Includes the first and finally, to determine the surface temperature by extrapolating before applying the sensor (tp-before) at a certain point calibration.

Surface temperature measured by extrapolating should remain within $\pm 2^{\circ}\text{C}$ of the nominal temperature, in order to avoid the correction that occurs due to the difference between the nominal point and surface temperature.

2. The following step is leaning contact thermometer on the surface of the reference blocks for purpose of measuring and obtaining data read from the thermometer.

Contact thermometer is then applied manually. Following the example of the project Thermometry 635 [4] and a bilateral comparison BNM-LNE and OMH [9] should have recorded three measurements performed at the calibration point, and the mean to define the temperature (t_k). Or may be several measurements: "The procedure can still be adjusted taking into account that some sensors require more measurements; measurement with surface sensor operator repeated until it is determined that the measured value is stable". [8]

3. After removing the contact thermometer (sensor), the surface temperature is once again determined by extrapolating ($t_{p-after}$). The average surface temperature determined by extrapolating is defining reference temperature (t_p), which is the basic value between ($t_{p-before}$) and ($t_{p-after}$).

4. Thus measurement of the temperature of the reference surface and of the calibration object - contact thermometer (sensor) is performed as described, and one cycle when reference body is in the "lower" position (Figure 8.), and then measuring at the same calibration point when the reference surface is in "upper" position (Figure 9.).

In this way, when the reference surface is in the "lower" position, the ambient temperature just above the reference surface is practically heated to a given temperature, and also contact thermometer which placed just above the reference surface is "preheated" in this way. In this way after leaning thermometer to the reference board it "takes" less heat from the reference board.

Time se željelo postići smanjenje razlike izmjernih rezultata vrijednosti temperature referentne površine i vrijednosti temperature očitane sa kontaktog termometra, te na taj način potvrditi hipotezu o postizanju boljih približnijih rezultata mjerena. Razlika temperatura se javlja kod prislanjanja kontaktog termometra i na taj način narušavanja temperaturnog polja na samoj referentnoj površini.

Pretpostavka je bila da će razlika temperatura očitanih vrijednosti sa termometra i referentne ploče (dobijeno ekstrapoliranjem) i izmjernih na višim kalibracionim tačkama biti znatno veća. Pretpostavka je bila i da će razlika temperatura posebno biti izražena u slučaju kada nema uticaja ambijentne temperature tik iznad površine referentnog bloka odnosno kada nema „predgrijavanja“ referentne površine i kontaktog termometra.

3. MATEMATIČKI MODEL PRORAČUNA MJERNE NESIGURNOSTI

- Zavisnost senzora temperature (T_c) o temperaturi površine (T_s) i ambijentnoj temperaturi (T_{amb})**

$$E = t_s - t_p \quad (3)$$

gdje je:

t_p - temperatura površine određena ekstrapolacijom i

t_s - očitana temperatura senzora.

Nesigurnost vezana za odstupanje E je:

$$u^2(E) = u^2(t_p) + u^2(t_s) \quad (4)$$

- Uticaj referentne temperature površine (t_p)**

Temperatura t_p se određuje metodom ekstrapolacije prema formuli:

$$t_p = \frac{(t_{sup} - t_{inf}) \cdot (e - h_{inf})}{(h_{sup} - h_{inf})} + t_{inf} \quad (5)$$

gdje je:

t_{inf}, t_{sup} - Temperature u tijelu (dalja i bliža od referentne površine)

h_{inf}, h_{sup} - Vertikalne pozicije otvora u osi cilindrične referentne površine

e - Debljina referentne ploče (tijela)

Ako: $t_{inf} = t_i + c_{i-cal} + c_{i-stab} + c_{i-hom} + c_{i-drift}$
 i $t_{sup} = t_j + c_{j-cal} + c_{j-stab} + c_{j-hom} + c_{j-drift}$

The aim was to achieve a reduction of difference measured results of the reference surface temperature and temperature values read out of with contact thermometer, thus confirm the hypothesis of achieving better or closer measurement results. Temperature difference occurs when leaning contact thermometer and thus distortion of the temperature field on the reference surface.

The assumption was that the temperature difference in readings from a thermometer and the reference board (obtained by extrapolating) that are measured at the higher calibration point will be much higher. The assumption was also that the temperature difference will be particularly obvious in the case when there is no influence of ambient temperature just above the surface of the reference block or when there is no "preheat" of the reference surface and the contact thermometer.

3. MATEMATIČKI MODEL PRORAČUNA MJERNE NESIGURNOSTI

- Zavisnost senzora temperature (T_c) o temperaturi površine (T_s) i ambijentnoj temperaturi (T_{amb})**

$$E = t_s - t_p \quad (3)$$

where:

t_p – temperature of surface obtained by extrapolation and

t_s – Temperature of sensor

Uncertainty related to deviation E:

$$u^2(E) = u^2(t_p) + u^2(t_s) \quad (4)$$

- Influence of temperature of reference surface (t_p)**

Temperature t_p is determined by extrapolation method according to equation:

$$t_p = \frac{(t_{sup} - t_{inf}) \cdot (e - h_{inf})}{(h_{sup} - h_{inf})} + t_{inf} \quad (5)$$

where:

t_{inf}, t_{sup} - Temperature within body (further and closer of reference surface)

h_{inf}, h_{sup} - Vertical position of openings in axis of cylindrical reference surface

e - The thickness of the reference plate (body)

If: $t_{inf} = t_i + c_{i-cal} + c_{i-stab} + c_{i-hom} + c_{i-drift}$
 and $t_{sup} = t_j + c_{j-cal} + c_{j-stab} + c_{j-hom} + c_{j-drift}$

Onda je:

t_x - Srednja izmjerena temperatura sa senzorom x u referentnoj ploči(tijelu),

x može biti x = i ili j (senzor koji je bliže ili dalje od referente površine)

c_{x-stab} . - Korekcija u odnosu na kalibraciju senzora x

c_{x-hom} . - Korekcija u odnosu na nehomogenost temperature u okolini senzora x

$c_{x-drift}$. - Korekcija u odnosu na drift senzora x

h_{sup}, h_{inf} - Vertikalna pozicija otvora u osi cilindrične referentne površine

U odnosu na specificirane doprinose mjerna nesigurnost, vezana za temperaturu referentne površine (specimena) prema [6], iznosi:

$$\begin{aligned} u^2(t_p) &= \left(\frac{\delta t_p}{\partial t_i}\right)^2 \cdot u^2(t_i) + \left(\frac{\delta t_p}{\partial c_{i-cal}}\right)^2 \cdot u^2(c_{i-cal}) + \left(\frac{\delta t_p}{\partial c_{i-stab}}\right)^2 \cdot u^2(c_{i-stab}) + \left(\frac{\delta t_p}{\partial c_{i-hom}}\right)^2 \cdot u^2(c_{i-hom}) + \left(\frac{\delta t_p}{\partial c_{i-drift}}\right)^2 \cdot u^2(c_{i-drift}) + \left(\frac{\delta t_p}{\partial t_j}\right)^2 \cdot u^2(t_j) + \left(\frac{\delta t_p}{\partial c_{j-cal}}\right)^2 \cdot u^2(c_{j-cal}) + \\ &\quad \left(\frac{\delta t_p}{\partial c_{j-stab}}\right)^2 \cdot u^2(c_{j-stab}) + \left(\frac{\delta t_p}{\partial c_{j-hom}}\right)^2 \cdot u^2(c_{j-hom}) + \left(\frac{\delta t_p}{\partial c_{j-drift}}\right)^2 \cdot u^2(c_{j-drift}) + \left(\frac{\delta t_p}{\partial e}\right)^2 \cdot u^2(e) + \left(\frac{\delta t_p}{\partial h_{inf}}\right)^2 \cdot u^2(h_{inf}) + \left(\frac{\delta t_p}{\partial h_{sup}}\right)^2 \cdot u^2(h_{sup}) \end{aligned} \quad (6)$$

sa:

with:

$$\frac{\delta t_p}{\partial t_i} = \frac{\delta t_p}{\partial c_{i-cal}} = \frac{\delta t_p}{\partial c_{i-stab}} = \frac{\delta t_p}{\partial c_{i-hom}} = \frac{\delta t_p}{\partial c_{i-drift}} = \frac{h_{sup}-e}{h_{sup}-h_{inf}} \quad (7)$$

$$\frac{\delta t_p}{\partial t_j} = \frac{\delta t_p}{\partial c_{j-cal}} = \frac{\delta t_p}{\partial c_{j-stab}} = \frac{\delta t_p}{\partial c_{j-hom}} = \frac{\delta t_p}{\partial c_{j-drift}} = \frac{e-h_{inf}}{h_{sup}-h_{inf}} \quad (8)$$

$$\frac{\delta t_p}{\partial h_{inf}} = \frac{(t_{inf}-t_{sup}) \cdot (h_{sup})}{(h_{sup}-h_{inf})^2}; \quad \frac{\delta t_p}{\partial h_{sup}} = \frac{(t_{sup}-t_{inf}) \cdot (e-h_{inf})}{(h_{sup}-h_{inf})^2}; \quad \frac{\delta t_p}{\partial e} = \frac{t_{sup}-t_{inf}}{h_{sup}-h_{inf}} \quad (9)$$

Pripadajući doprinosi mjerne nesigurnosti za procjene vrijednosti pojedinih uticaja, su specificirani za kalibracionu aparaturu, a izražavaju se prema datim formulama.

- **Uticaj temperature instrumenta (t_s)**

Temperatura senzora t_s se određuje prema jednačini:

$$t_s = t_{s-ocit.} + c_{rezol.} + c_{amb.} + c_{materijal} + c_{tp-nazad.} + c_{deb.} + c_{pov.} + c_{operat.} \quad (10)$$

gdje su:

$t_{s-ocit.}$ - Srednja očitana temperatura kontaktnog senzora

$c_{rezol.}$ - Korekcija u odnosu na rezoluciju instrumenta

$c_{amb.}$ - Korekcija u odnosu na uticaj ambijentne temperature na mjerjenje u toku kalibracije

Than:

t_x - Mean temperature measured by sensor x in reference plate (body),

x may be x = i or j (sensor that is closer or further of referece surface

c_{x-stab} - Correction due to calibration of sensor x

c_{x-hom} - Correction related to inhomogeneity of temperature around sensor x

$c_{x-drift}$ - Correction related to drift of senzor x

h_{sup}, h_{inf} - Vertical position of openings in axis of cylindrical reference surface

In relation to specified contributions the measurement uncertainty related to reference surface (specimen) temperature according to [6], is:

$$\frac{\delta t_p}{\partial t_i} = \frac{\delta t_p}{\partial c_{i-cal}} = \frac{\delta t_p}{\partial c_{i-stab}} = \frac{\delta t_p}{\partial c_{i-hom}} = \frac{\delta t_p}{\partial c_{i-drift}} = \frac{h_{sup}-e}{h_{sup}-h_{inf}}$$

$$\frac{\delta t_p}{\partial t_j} = \frac{\delta t_p}{\partial c_{j-cal}} = \frac{\delta t_p}{\partial c_{j-stab}} = \frac{\delta t_p}{\partial c_{j-hom}} = \frac{\delta t_p}{\partial c_{j-drift}} = \frac{e-h_{inf}}{h_{sup}-h_{inf}}$$

$$\frac{\delta t_p}{\partial h_{inf}} = \frac{(t_{inf}-t_{sup}) \cdot (h_{sup})}{(h_{sup}-h_{inf})^2}; \quad \frac{\delta t_p}{\partial h_{sup}} = \frac{(t_{sup}-t_{inf}) \cdot (e-h_{inf})}{(h_{sup}-h_{inf})^2}; \quad \frac{\delta t_p}{\partial e} = \frac{t_{sup}-t_{inf}}{h_{sup}-h_{inf}}$$

$$\frac{\delta t_p}{\partial t_i} = \frac{\delta t_p}{\partial c_{i-cal}} = \frac{\delta t_p}{\partial c_{i-stab}} = \frac{\delta t_p}{\partial c_{i-hom}} = \frac{\delta t_p}{\partial c_{i-drift}} = \frac{h_{sup}-e}{h_{sup}-h_{inf}} \quad (7)$$

$$\frac{\delta t_p}{\partial t_j} = \frac{\delta t_p}{\partial c_{j-cal}} = \frac{\delta t_p}{\partial c_{j-stab}} = \frac{\delta t_p}{\partial c_{j-hom}} = \frac{\delta t_p}{\partial c_{j-drift}} = \frac{e-h_{inf}}{h_{sup}-h_{inf}} \quad (8)$$

$$\frac{\delta t_p}{\partial h_{inf}} = \frac{(t_{inf}-t_{sup}) \cdot (h_{sup})}{(h_{sup}-h_{inf})^2}; \quad \frac{\delta t_p}{\partial h_{sup}} = \frac{(t_{sup}-t_{inf}) \cdot (e-h_{inf})}{(h_{sup}-h_{inf})^2}; \quad \frac{\delta t_p}{\partial e} = \frac{t_{sup}-t_{inf}}{h_{sup}-h_{inf}} \quad (9)$$

The corresponding contributions to the measurement uncertainty for the valuation of individual impact, are specified for the calibration apparatus, and expressed according to the formulas.

- **Influence of the instrument temperature (t_s)**

Temperature of sensor t_s is defined according to:

$$t_s = t_{s-ocit.} + c_{rezol.} + c_{amb.} + c_{materijal} + c_{tp-nazad.} + c_{deb.} + c_{pov.} + c_{operat.} \quad (10)$$

where:

$t_{s-ocit.}$ - Mean measured temperature of contact sensor

$c_{rezol.}$ - Correction in relation to the resolution of the instrument

$c_{amb.}$ - Correction with regard to the impact of ambient temperature on measurement during calibration

$c_{materijal}$ - Korekcija u odnosu na termičku provodnost vezanu za vrstu materijala od kojeg je napravljena referentna ploča (tijelo) [27]

$c_{tp-nazad}$ - Korekcija u odnosu na promjene u temperaturi referentne površine kod stacionarnog stanja nakon izvlačenja senzora koji se kalibrira

$c_{deb.}$ - Korekcija uslijed razlike u debljinu materijala u odnosu na referentne uvjete

$c_{pov.}$ - Korekcija uslijed razlike kontaktnog otpora u odnosu na referentne uvjete

$c_{operat.}$ - Korekcija u odnosu na efekat operatera

(*) Nesigurnosti $c_{deb.}$, $c_{pov.}$, $c_{operat.}$ trenutno nisu uzete u obzir.

Na osnovu specificiranih doprinosa u odnosu na E dobije se:

$$u^2(t_s) = u^2(t_{s-očit.}) + u^2(c_{rezol.}) + u^2(c_{amb.}) + u^2(c_{materijal.}) + u^2(c_{tp-nazad.}) + \\ u^2(c_{deb.}) + u^2(c_{pov.}) + u^2(c_{operat.}) \quad (11)$$

Specificirani doprinosi, procjenjene vrijednosti, vrste distribucije vjerovatnoće, standardne nesigurnosti, koeficijenti osjetljivosti prema jednačinama od (3) do (11) će biti tabelarno prikazane u poglavlju 4 u četiri kalibracione tačke, da bi se dobole i predstavile pojedinačne vrijednosti doprinosa nesigurnosti. Njihovim uvrštavanjem u jednačinu (6) dobija se mjerna nesigurnost metode.

Na ovom principu su izvedeni svi proračuni potrebni za izračunavanje proširene (ukupne) mjerne nesigurnosti što je i predmet ovog rada.

$c_{materijal}$ - Correction in respect of thermal conductivity of type of material from which the reference plate (body) is made [27]

$c_{tp-nazad}$ - Correction in relation to changes in the temperature of the reference surface at steady state after the draw sensor that is calibrated

$c_{deb.}$ - Correction due to differences in the thickness of the material in relation to the reference conditions

$c_{pov.}$ - Correction due to differences of the contact resistance in comparison to the reference conditions

$c_{operat.}$ - Correction in relation to the effect of the operator

(*) Uncertainties $c_{deb.}$, $c_{pov.}$, $c_{operat.}$ currently not taken into account.

Based on the specified contributions in relation to E is:

The specified contributions, estimated value, types of probability distributions, standard uncertainties, sensitivity coefficients of the equations of (3) to (11) will be given in tables of results. Their inclusion in the equation (6) gives the uncertainty methods.

On this principle are done all calculations required to calculate the extended (overall) measurement uncertainty which is needed to be add to results and is the subject of this paper.

**4. REZULTATI KALIBRACIJE I
PROCJENA UKUPNE MJERNE
NESIGURNOSTI NA
KALIBRACIONOJ TAČKI 300 °C**

A) Kada je referentna površina u „donjem“ položaju

**4. CALIBRATION RESULTS AND
ESTIMATION OF MEASUREMENT
UNCERTAINTY AT CALIBRATION
POINT 300 °C**

A) When reference surface is in the „lower“ position

Tabela 1. Doprinosi mjernoj nesigurnosti referentne površine kada je referentno tijelo/površina u „donjem“ položaju na kalibracionoj tački 300 °C

Table 1. Contributions to measurement uncertainty of reference surface when reference body/surface is in the „lower“ position at calibration point 300 °C

X _i	Procjena x _i Estimation x _i	Raspodjela Distribution	St.nes u(x _i) St.uncert. u(x _i)	Koef.osjet. Sensitivity coef. c _i	Dopr. Contributions c _i ·u(x _i)
t _i	300,57 °C	N	0,04 °C	0,391	0,02
C _{i-cal}	1,67 °C	N	0,42 °C	0,391	0,17
C _{i-stab}	0 °C	P	0,05 °C	0,391	0,02
C _{i-hom}	0 °C	P	0,05 °C	0,391	0,02
C _{i-drift}	0 °C	P	-	0,391	-
t _j	299,65 °C	N	0,03 °C	1,391	0,04
C _{j-cal}	1,67 °C	N	0,42 °C	1,391	0,59
C _{j-stab}	0 °C	P	0,05 °C	1,391	0,07
C _{j-hom}	0 °C	P	0,05 °C	1,391	0,07
C _{j-drift}	0 °C	P	-	1,391	-
e	50,0 mm	N	0,10 mm	0,027 °C/mm	0,01
h _{inf}	2,0 mm	N	0,10 mm	0,028 °C/mm	0,01
h _{sup}	36,5 mm	N	0,10 mm	0,037 °C/mm	0,01
t _p	300,96 °C	/	/	/	0,63 °C

Tabela 2. Doprinosi mjernoj nesigurnosti kontaktnog senzora na kalibracionoj tački 300 °C kada je referentno tijelo/ površina u „donjem“ položaju

Table 2. Contributions to measurement uncertainty of contact sensor at calibration point 300 °C when the reference body/ surface in the „lower“ position

X _i	Procjena x _i Estimation x _i	Raspodjela Distribution	St.nes u(x _i) St.uncert. u(x _i)	Koef.osjet. Sensitivity coef. c _i	Dopr. Contributions c _i ·u(x _i)
t _{s-očit}	299,88 °C	N	0,23 °C	1	0,23 °C
c _{rezol.}	0 °C	P	0,33 °C	1	0,33 °C
c _{amb.}	0 °C	P	0,11 °C	1	0,11 °C
c _{materijal.}	0 °C	P	0,05 °C	1	0,05 °C
c _{tp-nazad}	0 °C	P	0,07 °C	1	0,07 °C
t _s	299,88 °C	/	/	/	0,43 °C

$$u^2(E) = u^2(t_k) + u^2(t_p)$$

$$u(E) = u(E) = \sqrt{u^2(t_k) + u^2(t_p)} = 0,76 \text{ } ^\circ\text{C}$$

B) Kada je referentna površina u „gornjem“ položaju

B) When reference surface is in the „upper“ position

Tabela 3. Doprinosi mjernoj nesigurnosti referentne površine kada je referentno tijelo/površina u „gornjem“ položaju na kalibracionoj tački 300 °C

Table 3. Contributions to measurement uncertainty of reference surface when reference body/surface is in the „upper“ position at calibration point 300 °C

X _i	Procjena x _i Estimation x _i	Raspodjela Distribution	St.nes u(x _i) St.uncert. u(x _i)	Koef.osjet. Sensitivity coef. c _i	Dopr. Contributions c _i ·u(x _i)
t _i	295,71 °C	N	0,05 °C	0,391	0,02
C _{i-cal}	1,67 °C	N	0,42 °C	0,391	0,17
C _{i-stab}	0 °C	P	0,05 °C	0,391	0,02
C _{i-hom}	0 °C	P	0,05 °C	0,391	0,02
C _{i-drift}	0 °C	P	-	0,391	-
t _j	291,28 °C	N	0,03 °C	1,391	0,04
C _{j-cal}	1,67 °C	N	0,42 °C	1,391	0,59
C _{j-stab}	0 °C	P	0,05 °C	1,391	0,07
C _{j-hom}	0 °C	P	0,05 °C	1,391	0,07
C _{j-drift}	0 °C	P	-	1,391	-
e	50,0 mm	N	0,10 mm	0,129 °C/mm	0,02
h _{inf}	2,0 mm	N	0,10 mm	0,136 °C/mm	0,02
h _{sup}	36,5 mm	N	0,10 mm	0,179 °C/mm	0,02
t _p	291,22 °C	/	/	/	0,63 °C

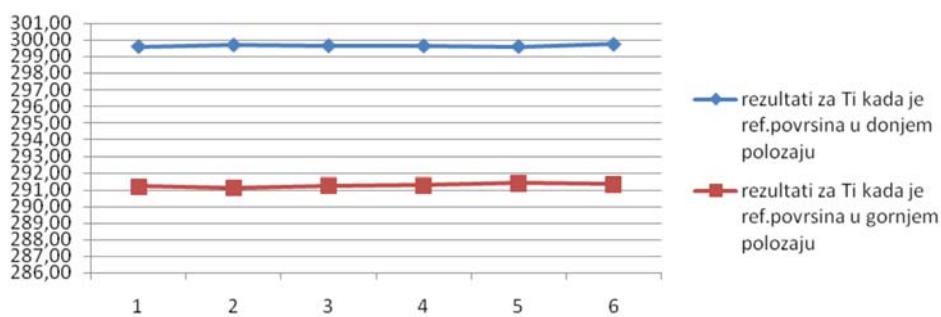
Tabela 4: Doprinosi mjernoj nesigurnosti kontaktnog senzora na kalibracionoj tački 300 °C kada je referentno tijelo/površina u „gornjem“ položaju

Table 4: Contributions to measurement uncertainty of contact sensor at calibration point 300 °C when the reference body/ surface in the „upper“ position

X _i	Procjena x _i Estimation x _i	Raspodjela Distribution	St.nes u(x _i) St.uncert. u(x _i)	Koef.osjet. Sensitivity coef. c _i	Dopr. Contributions c _i ·u(x _i)
t _{s-očit}	289,87 °C	N	0,16 °C	1	0,16 °C
c _{rezol.}	0 °C	P	0,33 °C	1	0,33 °C
c _{amb.}	0 °C	P	0,11 °C	1	0,11 °C
c _{materijal.}	0 °C	P	0,24 °C	1	0,24 °C
c _{tp-nazad}	0 °C	P	0,13 °C	1	0,13 °C
t _s	289,87 °C	/	/	/	0,41 °C

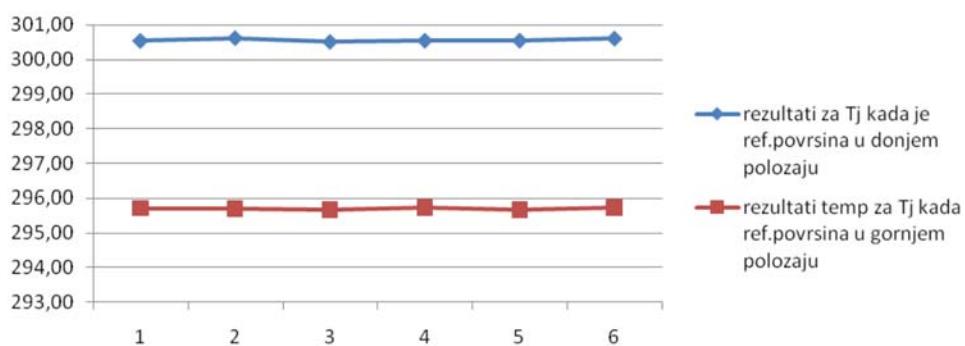
$$u^2(E) = u^2(t_k) + u^2(t_p)$$

$$u(E) = \sqrt{u^2(t_k) + u^2(t_p)} = 0,75 \text{ } ^\circ\text{C}$$



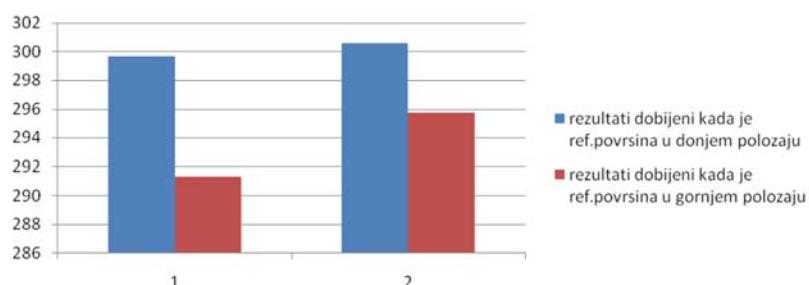
Dijagram 1. Prikaz razlika srednjih izmjerениh vrijednosti temperatura (t_{prije} i $t_{poslije}$) za T_i - termoelement bliži ref.površini mjereno u donjem i gornjem položaju referentne površine. (300 °C)

Chart 1. Display of differences in mean values of measured temperature (t_{before} and t_{poslje}) for T_i - thermocouple closer to reference surface, measured in the lower and upper position of the reference surface. (300 °C)



Dijagram 2. Prikaz razlika srednjih izmjerenih vrijednosti temperatura (t_{prije} i $t_{poslije}$) za T_j - termoelement dalji od ref.površine mjereno u donjem i gornjem položaju referentne površine (300 °C).

Chart 2. Display of differences in mean values of measured temperature (t_{before} and t_{poslje}) for T_j - thermocouple further from reference surface, measured in the lower and upper position of the reference surface (300 °C).



Dijagram 3. Prikaz rezultata srednjih vrijednosti temperature za T_i i T_j (termoelementi dalji i bliži referentnoj površini) korišteni za ekstrapoliranje temperature površine kada se referentna površina nalazi u donjem pa u gornjem položaju. (300 °C)

Chart 3. Results of mean values for temperature T_i and T_j (thermocouples further and closer to the reference surface) are used to extrapolate the surface temperature when the reference area is in the lower and in the upper position (300 °C).

5. ZAKLJUČCI

- a) Istraživanje je provedeno u cilju uspostavljanja vlastite procedure za kalibraciju kontaktnih termometara za mjerjenje temperature čvrste površine.
- b) Da se jasno definiraju i kvantifikuju doprinosi mjernoj nesigurnosti pri kalibraciji kontaktnih termometara za mjerjenje temperature čvrste površine.
- c) Da su sprovedene prve kalibracije na prototipu aparature-etalona za kalibraciju kontaktnih termometara za mjerjenje temperature čvrste površine, a u smislu pripreme za validaciju same aparature.

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- 5. CONCLUSIONS**
- a) The survey was conducted in order to establish own procedures for the calibration of contact thermometers for temperature measurement on solid surface.
 - b) In order to clearly define and quantify the contributions to measurement uncertainty during the calibration of contact thermometers for temperature measurement of solid surface.
 - c) To carried out the first calibration on the prototype apparatus-standard for calibration of contact thermometers for solid surface temperature measurement, and in terms of preparation for the validation of the apparatus.

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