10.2478/msr-2013-0007

A Proposal for Simplifying the Method of Evaluation of Uncertainties in Measurement Results

M. Kušnerová[1,2], J. Valíček[1,2], M. Harničárová[3], T. Hryniewicz[4], K. Rokosz[4], Z. Palková[5], V. Václavík[6], M. Řepka[7], M. Bendová[8]

[1]Institute of Physics, Faculty of Mining and Geology, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic, milena.kusnerova@vsb.cz, jan.valicek@vsb.cz
[2]RMTVC, Faculty of Metallurgy and Materials Engineering, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic, milena.kusnerova@vsb.cz, jan.valicek@vsb.cz
[3]Nanotechnology Centre, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic, marta.harnicarova@vsb.cz
[4]Koszalin University of Technology, Division of Surface Electrochemistry and Technology, Racławicka 15-17, PL 75-620 Koszalin, Poland, tadeusz.hryniewicz@tu.koszalin.pl, rokosz@tu.koszalin.pl
[5]Department of Electrical Engineering, Automatics and Informatics of the Technical faculty, Slovak University of Agriculture, Trieda A. Hlinku 2, 949 76 Nitra, Slovakia, Zuzana.Palkova@uniag.sk
[6]Institute of Environmental Engineering, Faculty of Mining and Geology, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic, vojtech.vaclavik@vsb.cz
[7]Institute of Economics and Control Systems, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic, michal.repka@vsb.cz
[8]Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use, Faculty of Mining and Geology, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic, miroslava.bendova@vsb.cz

The paper deals with the innovative ways of nonstandard, simplifying applications of the valid method for evaluating uncertainties in measurement results and with the definition of conditions of their usability. The evaluation of a substitute criterion for measurement accuracy by means of a relative difference between the measurand and its reference value is proposed. This nonstandard relative uncertainty is comparable with the overall relative standard uncertainty in the measurement result, and thus the evaluation of it enables other simplifications in the calculations of measurement result uncertainties. The use of the simplified evaluation of measurement results is illustrated in two experiments in measurement of the coefficient of thermal conductivity of an insulating material newly developed for the needs of building practice, namely measurement using commercial instruments, and measurement using a newly developed original measuring instrument.

Keywords: Measurements, relative nonstandard uncertainty, verification

1. INTRODUCTION

MODERNIZATION and above all simplification of the valid method for the evaluation of uncertainties in measurement results should be gradually required by engineering practice. However, the situation is quite different. The determination of measurement result uncertainties, although officially prescribed by accreditation bodies, is not carried out in the majority of technical laboratories at all. This is caused by the diversity of measurement methods, measuring instruments, tests and complicated methods for the evaluation of measurement result uncertainties, by the fact that owners of measurement and test results are directly contracting authorities for these activities, and also by the fact that customers do not require any expression of uncertainties. On the other hand, even in an unambiguous, simple and evidential method, merely mathematized estimates are used, not perfectly accurate results (even in the case of statistical calculations according to Gauss's uncertainty propagation law). That is why at present, according to basic documents on metrology valid in the EU countries and USA [1-4], modifications of uncertainties with a rather high value of maximum permissible error are adopted. It is included double into the final result, i.e. expanded uncertainty in the result of overall measurement, which increases the probability dispersion to 95 %, and thus the reliability of declared values as well. Owing to the insufficient number of measurements ($n < 10$), the measurement result uncertainty is expanded too, i.e. it is multiplied by the correction factor for a qualified estimate k_0 (e.g. for $n = 2; \dots ; 9$, $k_0 = 7; 2.3; 1.7; 1.4; 1.3; 1.3; 1.2; 1.2$).

2. THEORETICAL PART

On the basis of the standard ČSN ISO 01 0115, measurement quality is characterised by means of 4 measurement characteristics: Measurement result accuracy is defined as closeness of agreement between the measurement result and the ideal true (real reference) value of the measurand. Measurement result repeatability as closeness of agreement between the results of consecutive measurements of the same measurand carried out under the same conditions. Measurement result reproducibility as closeness of agreement between the results of measurement of the same quantity carried out under changed measurement conditions. Measurement result uncertainty as a characteristic associated with the measurement result that characterises the dispersion of values.

Eurolab (Organization for testing in Europe) appointed many expert commissions that began to deal with the issues of measurement and testing result uncertainties very consistently in our country in the year 1992; some of them already make result uncertainty evaluation in the area of their activities. However, these are problems that require a complex and long-term solution. In the 1980's, a proposal for a conceptual change in the "method for the evaluation of measurement results and their uncertainties" was submitted. In the years 1990 to 1993, the document "Guide to the Expression of Uncertainty in Measurement" with supplements was published by the Western European Calibration Cooperation (WECC); so far, it has been applied as a unifying document and has been innovated especially for the purpose of certification [5-7].

2.1. Conversion of indirect measurement result uncertainty to direct measurement result uncertainty

The simplification of evaluation of the type A statistical uncertainty in the direct measurement result cannot be discussed [1-4].

The type A relative standard uncertainty in the direct measurement result can be then evaluated as a ratio (1)

$$\rho_{Aa} = \frac{u_{Aa}}{\bar{a}} \cdot 100\% \qquad (1)$$

Furthermore, let f be an indirectly measured physical quantity that depends on directly measured partial physical quantities a, b, c, i.e. $f = f(a, b, c, \dots)$. For the mean value $\bar{f}$ of the overall measurement result, a relation is valid; $\bar{f} = f\left(\bar{a}, \bar{b}, \bar{c}, \dots\right)$ being mean values of the results of partial direct measurements. The physical quantity f is formally presented by notation of an interval with a mean value $\bar{f}$ and uncertainty (2)

$$f = \bar{f} \pm u_{Af} \qquad (2)$$

The type A absolute standard uncertainty u_{Af} in the indirect measurement result can be classically evaluated for the finite number of measurements n according to Gauss's uncertainty propagation law (3)

$$u_{Af} = \sqrt{\left(\frac{\partial f}{\partial a} \cdot u_{Aa}\right)^2 + \left(\frac{\partial f}{\partial b} \cdot u_{Ab}\right)^2 + \left(\frac{\partial f}{\partial c} \cdot u_{Ac}\right)^2 + \dots} \qquad (3)$$

Then the type A relative standard uncertainty in the indirect measurement result can be analogically evaluated for the finite number of measurements n according to Gauss's uncertainty propagation law (4)

$$\rho_{Af} = \sqrt{\rho_{Aa}^2 + \rho_{Ab}^2 + \rho_{Ac}^2 + \dots} \qquad (4)$$

In this phase of the evaluation process, simplification can already be discussed. In the majority of practical examples of datasets, values of uncertainties in the results of partial direct measurements are not usually comparable. Of the total value of uncertainty in the indirect measurement result, the highest order values of uncertainties in the result of partial direct measurements, i.e. the least accurate measurements, are decisive. The lower order values of uncertainties in the results of partial direct measurements do not reflect the overall uncertainty in the indirect measurement result; they are negligible. A condition for the simplifying conversion of the calculation of the indirect measurement result uncertainty to the calculation of the direct measurement result uncertainty is thus comparability in order between applied uncertainties in the results of partial direct measurements at the same number of partial direct measurement repetitions. The method for the evaluation of direct measurement results is suitable, above all with regard to the very simple and fast, software-based processing of measurement results, especially in the case of a large number of partial measurement repetitions (measured data from a computer-controlled experiment).

2.2. Evaluation of type c combined standard uncertainty without covariance of sources of uncertainties

Most generally, type C overall uncertainty in the indirect measurement result is divided into two components, namely a statistical component, i.e. type A random uncertainty, and a non-statistical component, i.e. type B systematic uncertainty. In the majority of cases of practical measurements, sources of uncertainties depend on each other and contribute to the overall uncertainty in the measurement result more or less depending on how the individual uncertainties are combined. Calculations of the overall uncertainty in the indirect measurement result are then really very complicated not only mathematically, but also owing to the requirement for the current knowledge of used instrument equipment and the physical experience of the experimenter. Evaluation by means of the overall combined standard uncertainty in the indirect measurement result without covariance can be recommended, because on the basis of Gauss's uncertainty propagation law, it covers even very complicated cases of measurement, in which correlation effects between individual measurements and measurands appear. The combined standard uncertainty (type C) represents an overall value of uncertainty to be associated with the result of the measurement. This uncertainty is determined by the relation (5), it is combined from two components: type A (random uncertainty) and type B (systematic uncertainty). In the experiment (Chapter 3, Fig.1), the values of partial measurements significantly oscillate around the mean value of the measurement result. Therefore, the statistical uncertainty (type A) is not negligible due to the uncertainty of physical factors (type B). Thus, both absolute standard uncertainties u_{Af}, u_{Bf} can combine to create the combined absolute standard uncertainty u_{Cf}, in the result of direct as well as indirect measurement (5)

$$u_{Cf} = \sqrt{u_{Af}^2 + u_{Bf}^2} \tag{5}$$

and analogically, the combined relative standard uncertainty can be determined by means of relevant relative standard uncertainties (6)

$$\rho_{Cf} = \sqrt{\rho_{Af}^2 + \rho_{Bf}^2} \tag{6}$$

2.3. Evaluation of type b relative standard uncertainty in the measurement result without covariance of sources of uncertainties

Complications in the evaluation of the overall uncertainty in the direct and indirect measurement result may occur mainly due to the difficulty of evaluation of the type B systematic uncertainty. This principal uncertainty is estimated on the basis of knowledge of uncertainties in available information sources and their sensitivities, on the basis of information provided by manufacturers of measuring equipment, such as precision of commercial measuring instruments, uncertainties declared in engineering documentation (certificates, calibration certificates, technical standards, engineering tables), and on the basis of the experimenter's experience (e.g., what can play a role is a gross error in value reading, unsuitable selection of the measuring instrument, unsuitable preparation of measurement samples, and unsuitable choice of the measurement procedure, not keeping the conditions identical for repeated measurements, unsuitable ways of evaluating measurement results, e.g., due to wrong rounding and wrong data processing, and others) [8]. In the framework of simplifying the evaluation of measurement results, using the proposed substitute accuracy criterion given below the relative standard uncertainty can be "calculated" by means of the mean value $\overline{f}$ of measurement result, reliable reference value f_{reff} and statistical relative uncertainty ρ_{Af} in the measurement result as follows (7)

$$\rho_{fB} = \sqrt{\left(\frac{f_{reff} - \overline{f}}{f_{reff}}\right) - \left(\rho_{fA}^2\right)} \tag{7}$$

2.4. Estimation of overall maximum uncertainty in the measurement result

In the original "theory of errors in physical measurements" the absolute and the relative maximum uncertainty "errors", u_{fmax} and ρ_{fmax}, respectively, in the indirect measurement were introduced by means of algebraic sums of uncertainties in the results of partial directly measured physical quantities as follows (8)

$$\begin{aligned} u_{f\max} &= \left|\frac{\partial f}{\partial a}\right| \cdot u_a + \left|\frac{\partial f}{\partial b}\right| \cdot u_b + \left|\frac{\partial f}{\partial c}\right| \cdot u_c + \ldots \\ \ldots \wedge \rho_{f\max} &= \rho_a + \rho_b + \rho_c + \ldots \end{aligned} \tag{8}$$

If we compare both the statistical estimates of the uncertainty in the indirect measurement result by rearrangement to relative indirect measurement uncertainties (9)

$$\begin{aligned} \frac{u_{f\max}}{\overline{f}} &= \left|\frac{\partial f}{\partial a}\right| \cdot \frac{u_a}{\overline{f}} + \left|\frac{\partial f}{\partial b}\right| \cdot \frac{u_b}{\overline{f}} + \left|\frac{\partial f}{\partial c}\right| \cdot \frac{u_c}{\overline{f}} + \ldots \\ \ldots \wedge \frac{u_{f\max}}{\overline{f}} &= \frac{u_a}{\overline{a}} + \frac{u_b}{\overline{b}} + \frac{u_c}{\overline{c}} + \ldots \end{aligned} \tag{9}$$

we shall generally find that they are not physically comparable (10)

$$\left|\frac{\partial f}{\partial a}\right| \neq \frac{\overline{f}}{\overline{a}};\; \left|\frac{\partial f}{\partial b}\right| \neq \frac{\overline{f}}{\overline{b}};\; \left|\frac{\partial f}{\partial c}\right| \neq \frac{\overline{f}}{\overline{c}};\ldots \tag{10}$$

Physical laws are formulated in physical relations, in which the indirectly measured physical quantity is most frequently directly or indirectly dependent on partial directly measured physical quantities. In a physical law (relation, equation), a dependence which is more complicated than is direct or indirect dependence may, however, generally occur. Then mathematical formulations of compatibility of both the maximum uncertainties in statistical estimates do not correspond. Nevertheless, on condition that an indirectly measured physical quantity depends on partial directly measured physical quantities only directly or indirectly, the evaluation of measurement accuracy using the maximum uncertainty can be interpreted as having a much higher informative value than is the value provided by mere orientation estimation.

Similarly, in measurements the classical mean uncertainty in the indirect measurement result (3) can be compared with the maximum uncertainty in the indirect measurement result (8). Because $u_f \neq u_{f\,max}$ (11), $u_f < u_{f\,max,}$ the relation $u_{f\,max} = u_f + 2Q$ (12) holds true; $2Q$ being a difference between both the uncertainties being discussed (3), (8). According to the following equations (11), (12) the equation (13) can be developed.

$$\sqrt{\left(\frac{\partial f}{\partial a} \cdot u_a\right)^2 + \left(\frac{\partial f}{\partial b} \cdot u_b\right)^2 + \left(\frac{\partial f}{\partial c} \cdot u_c\right)^2 + \ldots} \neq \left|\frac{\partial f}{\partial a}\right| \cdot u_a + \left|\frac{\partial f}{\partial b}\right| \cdot u_b + \left|\frac{\partial f}{\partial c}\right| \cdot u_c + \ldots \tag{11}$$

$$\left(\left|\frac{\partial f}{\partial a}\right| \cdot u_a + \left|\frac{\partial f}{\partial b}\right| \cdot u_b + \left|\frac{\partial f}{\partial c}\right| \cdot u_c + \ldots\right)^2 = 2Q + \left(\frac{\partial f}{\partial a} \cdot u_a\right)^2 + \left(\frac{\partial f}{\partial b} \cdot u_b\right)^2 + \left(\frac{\partial f}{\partial c} \cdot u_c\right)^2 + \ldots \tag{12}$$

$$Q = \left|\frac{\partial f}{\partial a}\right| \cdot u_a \cdot \left|\frac{\partial f}{\partial b}\right| \cdot u_b + \left|\frac{\partial f}{\partial a}\right| \cdot u_a \cdot \left|\frac{\partial f}{\partial c}\right| \cdot u_c + \left|\frac{\partial f}{\partial b}\right| \cdot u_b \cdot \left|\frac{\partial f}{\partial c}\right| \cdot u_c + \ldots \tag{13}$$

Thus, it is always worth performing the simplification and the acceleration of evaluation of measurement results not on a general physical and exact statistical basis, but on a specific physical and practical basis. Therefore, it is of importance to carry out the comparison of the orders of uncertainties in partial measurement results, and after that to exclude those uncertainties in measurement results that have lower order values as negligible from the calculation of overall uncertainty in the indirect measurement result. On the contrary, the estimate of measurement accuracy with the maximum measurement result uncertainty has a higher, more reliable informative value than the estimate of measurement accuracy with the measurement result uncertainty presented as "exact minimum".

2.5. Evaluation of relative difference as relative nonstandard uncertainty in the measurement result

Let $\rho_{\Delta f}$, i.e. an absolute value of a difference between the mean value $\overline{f}$ of the result of direct or indirect measurement and its reliably given reference value f_{reff}, be related to this reference value (14)

$$\rho_{\Delta f} = \frac{\left| f_{reff} - \overline{f} \right|}{f_{reff}} \cdot 100\ \% \qquad (14)$$

This substitute criterion for the overall accuracy of measurement can be considered as corresponding to the type C combined relative standard uncertainty, provided that the type C uncertainty is accurately evaluated and that the evaluation of the relative difference is based on a reliable reference value (15)

$$\rho_{Cf} = \rho_{\Delta f} \qquad (15)$$

Calculation of the total measurement uncertainty (type C) is replaced with the relative difference. This replacement is simplistic, but, of course, it is not generally valid.

Based on the above-mentioned relation, other estimations of measurement results and their uncertainties can be simplified (16)

$$\frac{\sqrt{u_{Af}^2 + u_{Bf}^2}}{\overline{f}} = \frac{\left| f_{ref\ f} - \overline{f} \right|}{f_{ref\ f}} \qquad (16)$$

For instance, it is the difficult to obtain type B standard consistent uncertainty (17) that can be evaluated indirectly, i.e. by means of the mean value of the measurement result, relative difference $\rho_{\Delta f}$, and standard statistical uncertainty u_{Af}

$$u_{fB} = \sqrt{\left(\rho_{\Delta f} \cdot \frac{\overline{f}}{100} \right)^2 - u_{Af}^2} \qquad (17)$$

3. Experimental part

Below are presented two experiments carried out on a new insulating material using commercial instruments and an original instrument with the aim to evaluate the instrumental uncertainty in the developed instrument and to verify a reference value of the thermal-insulating properties of a newly developed material.

3.1. Verification of reference value of the thermal conductivity coefficient of building material

The reference value declared in engineering documentation is of high importance to the calculations of measurement results. The aim was to verify the reference value of the thermal conductivity coefficient declared directly by the manufacturer, namely for a transverse TM YTONG (lightweight concrete block) for building blocks P2 500 depending on material composition, density, moisture, and on specific sample thickness. The reference value of the coefficient $\lambda = 0.130$ W·m^{-1}·K^{-1} was verified by measurement using a commercial instrument Isomet 2114, and on the basis of data obtained from a set of measurements; a degree of agreement in the form of evaluation of uncertainties in measurement results was determined [9].

Isomet 2114 is a microprocessor-controlled commercial, hand-held instrument for direct measurement of, among other matters, the coefficient of thermal conductivity of materials by means of exchangeable probes. The given measurement was carried out by a surface probe with a built-in memory and calibration constants stored in the memory. In principle, the time dependence of thermal response on pulse transmitted from the heat flow into the material being measured is analysed. The heat flow is generated by dissipated electrical energy by means of the probe that is in direct contact with the material being measured. Temperature depending on resistance is sensed by a semiconductor sensor and a time change in the temperature is sampled in discrete points (regression polynomials that pass through the samples are constructed using the "least square method" and coefficients of relevant regression polynomials enable the analytical calculation of required parameters) [10-12]. For a measurement range from 0.015 to 0.700 W·m^{-1}·K^{-1}, Isomet 2114 guarantees the overall relative measurement uncertainty $\rho_{B\lambda} \approx 5$ %. On the whole, 34 repeated measurements were taken, i.e. a statistically sufficient number of measurements (Fig.1). The coefficient of thermal conductivity λ was evaluated with an accuracy of thousandths $\lambda = (0.119 \pm 0.010)$ W·m^{-1}·K^{-1} and with a statistical relative uncertainty in the measurement result $\rho_{A\lambda} = 8.4$ %. Uncertainties in measurement results exceeding the 5 % limit can be classified as measurement estimates suitable for engineering practice rather than laboratory. In a particular case, the measurement accuracy, however, corresponds to expectations, because the measured sample was made of a non-isotropic, nonhomogeneous material.

The overall combined uncertainty in the measurement result $\rho_{C\lambda} = 9.7$ % was then determined by means of statistical and instrumental uncertainty, and again, as a value lower than 10 %, it can be regarded as satisfactory for the needs of building practice. The relative difference was determined as follows: $\rho_{\Delta\lambda} = 8.5$ %.

The aim of verification of the reference value of the thermal conductivity coefficient thus was to calculate it theoretically (indirect measurement) on the basis of results of direct measurements:

for $\rho_{\Delta\lambda} = 9.7$ % : $\lambda_{ref} = 0.132$ W·m^{-1}·K^{-1}
for $\rho_{\Delta\lambda} = 8.5$ % : $\lambda_{ref} = 0.130$ W·m^{-1}·K^{-1}

It can be stated that the evaluation of "relative differences" as a substitute criterion for measurement accuracy is very accurate and that the mean value declared by the manufacturer of the material is reliably tabulated as well.

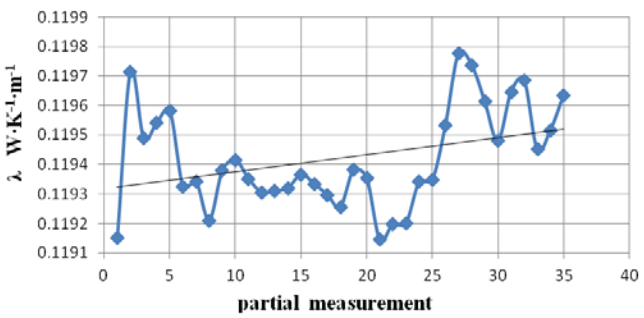

Fig.1. Time trend of partial measurement of thermal conductivity. Although the coefficient of thermal conductivity is referred to as a constant, it depends mainly on the temperature.

3.2. Evaluation of type b non-statistical uncertainty in the measurement result of newly developed instrument for measurement of material physical properties

In the framework of the project "New Technology for Thermal Insulating Plaster on the Base of PUR Waste" carried out in the years 2009-2010 in the Impulse programme (project Reg. No. Fi-IM5/015), physical and mechanical properties of an innovative building material (thermal insulating polyurethane plaster Daxner®) were measured using the newly developed measuring instrument. It was a case of sets of measurements of the thermal conductivity coefficient that were used not only for characterising the thermal insulating properties of the newly developed building material, but also as data for the evaluation of accuracy of the newly developed measuring instrument. A functional sample and a utility design of the given instrument and also a patent for the comparative method of measurement of material physical properties were submitted.

By means of the proposed nonstandard substitute criterion for measurement accuracy, an overall relative measurement uncertainty in this instrument was declared. The coefficient of thermal conductivity was measured with a three-decimal place accuracy

$$\lambda = (0.066 \pm 0.002)\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$$

and with a statistical relative uncertainty in the measurement result $\rho_{A\lambda} = 3.0\ \%$. The measurement was done on polyurethane samples having geometric dimensions of 15×15×2 cm in two sets of 50 and 52 partial measurements, at temperatures in the range from 24 °C to 34 °C. A comparative sample for the comparative measurement method was an asbestos sample of comparable geometric dimensions (with the tabulated value of thermal conductivity coefficient of 0.151 $\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$).

Furthermore, the thermal conductivity coefficient for the mentioned samples was measured (for the reliable comparison of results of measurements made by the newly developed instrument) in the state-owned enterprise Testing and Control Building Institute in Prague, using a thermal conductivity meter LaserComp Fox 801. According to a certificate (Protocol No. 070-038168 on the determination of thermal conductivity coefficient for thermal insulating polyurethane plaster), the mean value of the thermal conductivity coefficient of 0.06212 $\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$, the expanded uncertainty in the measurement result in ten-thousandths

$$\lambda = (0.0621 \pm 0.0026)\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$$

and the statistical relative uncertainty in the measurement result $\rho_{A\lambda} = 4.2\ \%$ were determined. The thermal conductivity coefficient was, in principle, verified using a top quality commercial instrument and a classical method of steady-state heat flow measurement.

4. Conclusion

The paper deals with the nonstandard simplification of the valid method for the evaluation of uncertainties in physical measurement results. On the basis of experimental data processing, it can be stated that especially the newly proposed substitute criterion for measurement accuracy, i.e. simplifying evaluation of overall relative uncertainty in the result of "relative difference" measurement, is very accurate. In this way, the reference value of the physical quantity declared by the manufacturer of the given building material as reliably tabulated value was verified. Furthermore, in this manner, the relative uncertainty in the result of measurement using the newly developed instrument was determined on the basis of a comparison between the value from measurement carried out using this original instrument and the reference value measured in a certified way. The measurement accuracy of the patented instrument (6.2 %) is comparable with the measurement accuracy of the commercial instruments, i.e. Isomet 2114 (5 %) and LaserComp Fox 801 (4.2 %).

Acknowledgment

This work was supported by the projects Moravian-Silesian region No. 0014/2012/RRC, RMTVC No. CZ.1.05/2.1.00/01.0040, ICT No. CZ.1.05/2.1.00/03.0082 and IT4 Innovations Centre of Excellence Project, reg. No. CZ.1.05/1.1.00/02.0070.

References

[1] Joint Committee for Guides in Metrology. (1995). Evaluation of measurement data - Guide to the expression of uncertainty in measurement. JCGM 100:2008. International Standardization Organization. Geneva, Switzerland.

[2] Bich, W., Cox, M. G., Harris, P. M. (2006). *Evolution of the Guide to the Expression of Uncertainty in Measurement*. Metrologia, 43(4), 161–166.

[3] Ellison, R. L.S., Rosslein, M. & Williams, A. (2000). *Quantifying uncertainty in analytical measurement.* EURACHEM/CITAC. (Tech. Rep. Guide CG4).

[4] Taylor, J.R. (1997). *An Introduction to Error Analysis. The Study of Uncertainties in Physical Measurements* (2nd ed.). Sausalito, USA: University Science Books.

[5] European Cooperation for Accreditation of Laboratories. (1997). *Expression of the Uncertainty of Measurement in Calibration*. EAL-R2.

[6] European Co-operation for Accreditation. (1999). *Expression of the Uncertainty of Measurement in Calibration*. EA 4/02.

[7] Yadav, S., Gupta, V.K., Prakash, O., & Bandyopadhyay, A.K. (2005). Evaluation of associated uncertainties in calibration of direct pressure indicating electromechanical devices. *Measurement Science Review*, 5(3), 104-114.

[8] Fornasini, P. (2008). *The Uncertainty in Physical Measurements. An Introduction to Data Analysis in the Physics Laboratory*. New York, USA: Springer Science + Business Media LLC.

[9] Yadav, S., Gupta, V. K. & Bandyopadhyay, A. K. (2010). Investigations on Measurement Uncertainty and Stability of Pressure Dial Gauges and Transducers. *Measurement Science Review*, 10(4), 130-135.

[10] Dudek, E., Mosiadz, M., & Orzepowski, M. (2007). Uncertainties of resistors temperature coefficients. *Measurement Science Review*, 7(3), 23-26.

[11] Ferson, S., Kreinovich, V., Hajagos, J., Oberkampf., W. & Ginzburg, L. (2007). *Experimental Uncertainty Estimation and Statistics for Data Having Interval Uncertainty*. Sandia National Laboratories. (SAND2007-0939).

[12] Kallner, A. (2006). Uncertainty in Measurement: Introduction and Examples. *Journal of the International Federation of Clinical Chemistry and Laboratory Medicine*, 13, 103-109.

Received September 10, 2012.
Accepted January 29, 2013.