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METHODOLOGY FOR DETERMINATION AND ASSESSMENT OF UNCERTAINTY SOURCES OF TEXTILE MATERIALS TOTAL THERMAL RESISTANCE

Abdurauf Abdurashidovich Abdukayumov[1], Ortagoli Sharipovich Hakimov[2]

[1]Uzbek Agency for standardization, metrology and certification Adress: 333-a, Farobiy st., 100049, Tashkent city, Republic of Uzbekistan, Phone: +998-98-368-07-37);
[2]Tashkent Institute of Architecture and Construction Adress: 13, Navoiy st., 100011, Tashkent city, Republic of Uzbekistan, Phone: +998-94-642-65-53).

Abstract: *The problems of improving of methods for determination of the total thermal resistance of textile materials are considered. A comparative analysis of the applied methods based on stationary and non-stationary heat exchange is performed. A higher accuracy of non-stationary methods based on measuring the cooling time of a heat cell with subsequent determination of the cooling rate and the total thermal resistance of the material under study is noted. A method is proposed for estimating the variance of the main values required for calculating the total thermal resistance of materials. The results of the study of the relationship between sources of uncertainty of the measurement result of the total thermal resistance of textile materials are presented.*
Keywords: *traceability, uncertainty, metrological, method, measurement, total, thermal, resistance.*

Аннотация: *Тўқимачилик материалларининг йиғинди иссиқлик қаршилигини аниқлаш усулларини такомиллаштириш муаммолари кўриб чиқилган. Стационар ва ностационар иссиқлик алмашинувига асосланган, қўлланиладиган усулларнинг қиёсий таҳлили амалга оширилган. Совитиш тезлигини ва ўрганилаётган материалнинг йиғинди иссиқлик қаршилигини аниқлаш орқали иссиқлик ҳужайрасининг совитиш вақтини ўлчашга асосланган ностационар усулларнинг юқорироқ аниқлиги қайд этилган. Материалларнинг йиғинди иссиқлик қаршилигини ҳисоблаш учун зарур бўлган асосий қийматларнинг дисперсиясини баҳолаш усули таклиф этилган. Тўқимачилик материалларининг йиғинди иссиқлик қаршилигини ўлчаш натижаларининг ноаниқлик манбалари орасидаги боғлиқликни ўрганиш натижалари келтирилган.*
Таянч сўзлар: *кузатилувчанлик, ноаниқлик, метрологик, усул, ўлчаш, йиғинди, иссиқлик, қаршилик.*

Аннотация: *Рассмотрены проблемы совершенствования методов определения суммарного теплового сопротивления текстильных материалов. Выполнен сопоставительный анализ применяемых методов, основанных на стационарном и нестационарном теплообмене. Отмечена более высокая точность нестационарных методов, основанных на измерении времени охлаждения тепловой ячейки с последующим определением темпа охлаждения и суммарного теплового сопротивления исследуемого материала. Предложен метод оценки дисперсии основных величин, необходимых для расчета суммарного теплового сопротивления материалов. Приведены результаты исследования взаимосвязи источников неопределенности результата измерения суммарного теплового сопротивления текстильных материалов.*
Ключевые слова: *прослеживаемость, неопределенность, метрологическая, метод, измерение, суммарное, тепловое, сопротивление.*

Introduction

At the present time, the quality, safety and competitiveness of products are becoming the most important factor in the dynamic and sustainable development of economic sectors, increasing the profitability and efficiency of production.

Achieving these goals is impossible without ensuring the accuracy, objectivity, reliability and comparability of measurement results used in various sectors of the economy and public administration.

Due to this, the Republic of Uzbekistan has adopted the Concept of development and improvement of the National system for ensuring the uniformity of measurements for the period 2019-

2023 [1], one of the goals of which is to maintain and develop the scientific, technical, regulatory and organizational foundations of metrological activities, to achieve international recognition of the results of measurements and tests conducted in the Republic of Uzbekistan.

In according to the documents in the field of Metrology and conformity assessment, metrological traceability, as well as the calculation of measurement uncertainty are the main requirements for measuring instruments used in testing laboratories to ensure the recognition of test reports in different countries.

The concepts of "metrological traceability" and "measurement uncertainty" appeared in metrological practice with the adoption of the international standard ISO/IEC 17025 [2], which describes requirements for the competence of testing and calibration laboratories. According to the international dictionary of Metrology [3], metrological traceability is a property of a measurement result by which the result can be correlated to a standard through a documented continuous chain of calibrations that cause measurement uncertainty.

In the Republic of Uzbekistan, the concepts of "measurement uncertainty" and "measurement traceability" are also fixed at the legislative level with the adoption of the "on Metrology" Law of the Republic of Uzbekistan in a new version (dated April 7, 2020, no.ZRU-614) [4].

Taking into account the above mentioned, to ensure the traceability of measurements performed during the products testing, in particular textile materials, assessing their uncertainty, which according to the [3] is defined as a non-negative parameter characterizing the dispersion of quantitative values, which can be attributed to the measurements based on the information.

One of the important indicators to be determined when testing a textile material is its total thermal resistance.

Research Methods and the Received Results

For the thermal properties of materials (for clothing and means of protection) measuring, devices based on the principles (methods) which can be divided to the following main groups [5-11] are used:

- methods based on steady-state, stationary heat transfer when in equal periods of time a material or system of materials has the same amount of heat. This group includes calorimetric and comparative methods;
- methods based on unsteady, non-stationary heat exchange, when different amounts of heat pass through the material at regular intervals. In this group the method of biocalorimetry is used the most widely.

The calorimetric method takes into account the amount of heat that has passed through the material sample. The basic principle of operation of the units is to create a heat flow directed perpendicular to the large faces of a flat sample of a certain thickness, followed by measuring the density of the stationary heat flow and temperatures on opposite sides of the sample.

Installations based on the stationary calorimetric method of measuring thermal conductivity have a system of heaters. In this case, the amount of heat is determined by the consumption of electricity in the heater for a certain period of time, the temperature on both sides of the material sample is determined by thermometers or thermocouples.

The disadvantage of the stationary calorimetric method is the dispersion (leakage) of the heat flow through the side surfaces of the walls and other parts of the device. These disadvantages of the stationary calorimetric method are eliminated in the stationary comparative method.

The comparative method [12] is based on taking into account the temperature distribution when a certain heat flow from the heater passes through samples of material with a pre-known thermal conductivity coefficient (a measure of thermal conductivity) and samples of the tested material during stationary heat exchange. As a measure of thermal conductivity, a plexiglass plate of a certain brand and specified thickness can be used.

The coefficient λ of the thermal conductivity of the test material in this method is determined by the equation (1):

$$\lambda = k \cdot \delta \cdot \left(\frac{\Delta t_1}{\Delta t_2}\right) \quad \text{W/(m·K)} \tag{1}$$

where *k* is the device constant equal to the ratio of the thermal conductivity coefficient of the standard sample to its thickness, W/(m^{2}K); δ is the sample thickness, mm; Δt_1 is the temperature difference at the sample surface from the heater side and the intermediate temperature measured between the other surface of the sample and the surface of the standard sample, ^{0}C; Δt_2 is the difference between the intermediate temperature between the surfaces of the sample and the standard sample and the external temperature (refrigerator temperature), ^{0}C.

The disadvantages of the stationary method are:

a) the difficulty of creating a uniform temperature field in the samples under study and accounting for heat losses; the inability to account for the influence of this inhomogeneity of the temperature field on the result of thermal conductivity measurement by theoretical calculations;

b) stationary methods can only determine the thermal conductivity;

c) stationary methods are associated with a significant time spent on conducting the experiment due to the duration of the process of entering the stationary thermal mode of the installation;

d) since the measurements are carried out during a stationary thermal process, and it occurs after 2-5 hours, the normalized humidity of the test material has time to change significantly during this time;

e) difficulties associated with the elimination of thermal resistance that occur at the points of contact of the sample with the surfaces of the heater and refrigerator. The error in determining the thermal conductivity due to the contact resistance can reach 10 ... 20% with a sample thickness of 1.5...3.0 mm and becomes even greater with an increasing in the thermal conductivity of the material under study.

These disadvantages are eliminated in the settings based on the regular mode method and developed by Prof. G. M. Kondratiev [13].

To measure the total thermal resistance of materials using the regular mode method, a bicalorimeter [13] is used. This devise consist of a hollow metal cylinder with heat insulators, thermocouples connected to a galvanometer and a stopwatch installed at the it's ends.

The device is based on a method that includes the measurement of cooling time of a hollow metal cylinder in a given range of temperature differences between the cylinder surface isolated by the test material and the surrounding air. The heated bicalorimeter, with the test material put on it, is cooled in stationary or moving air with a constant temperature. Measurement of the temperature difference between the device and the surrounding air at regular intervals determines the cooling rate, and then the total thermal resistance of the material.

The disadvantage of the bicalorimeter using is that it does not allow testing materials under a pressure equal to 0.2 kPa, regulated by GOST 20489 [14]. Pressure on the test material is necessary to reduce the pile layer of artificial and natural fur on a fabric basis.

The disadvantages of this setup are that the sample of the test material must be worn on the cylinder biocalorimetry and this sample should have a cylindrical shape of appropriate diameter and the same thickness over the entire surface, which is not always possible to implement especially for thick materials such as felt, leather and faux fur, multi-layered packages and products.

These disadvantages are eliminated in the device (more precisely, the installation) PTS-225 [14] for measuring the total thermal resistance.

The device like the bicalorimeter is based on the method of measuring of the device plate cooling time in a given range of temperature differences between the working surface of the plate isolated by the test material and the surrounding air.

In this case, it is assumed that the cooling of the plate is mainly due to the amount of heat transmitted by the working surface of the plate through the test material to the surrounding air. The amount of heat transmitted by other surfaces of the plate than the working one, through the heat insulator is considered relatively small compared to the first one. These assumptions are valid for materials whose total thermal resistance is at least an order of magnitude less than the total thermal resistance of the heat insulator.

However, the total thermal resistance which is made from many materials, such as felt, natural and artificial fur, multilayer bags and products is close to the total thermal resistance of heat insulators.

Therefore, these conditions are not met for such materials. Consequently, this leads to a narrowing of the dynamic measurement range of the device and an increase in the measurement error of the total thermal resistance. In addition, the pressure created by the pressure mechanism depends on the deformation of the elastic element and the accuracy of its calibration. This complicates the device and reduces the accuracy of reproducing the pressure equal to 0.2 kPa.

In this regard, to ensure the required accuracy in determining of the total thermal resistance of textile materials an important role is played by assessing the sources of its uncertainty.

The total thermal resistance (R_Σ) of the material is determined by the measured value of the cooling time (m) of the heat cell according to the equation [14]:

$$R_\Sigma = \frac{E}{\Phi \cdot K(m - B \cdot E)} \quad (2)$$

where $E = 3C_1/(3C_1 + C_2)$ is the coefficient; $\Phi = C_1/S$ is calorimeter heat factor, J/(m^{2}K); $K = 0{,}4 + [0{,}6/(1 + 2b/D)^2]$ is the coefficient that takes into account the heat flow dispersion in the sample; $m = \frac{ln\Delta T_1 - ln\Delta T_2}{\tau}$ is cooling rate, s^{-1}; B is correction coefficient that takes into account the heat flow dispersion in the calorimeter, s^{-1}; C_1 is total heat capacity of the plate, j / K; C_2 is total heat capacity of the test material; $C_2 = c_2 \cdot \rho_S \cdot S$, $c_2 = 1{,}675 \cdot 10^3$ J/kg·K; c_2 is specific heat capacity of organic materials; ρ_s is surface density of the test material, kg/m^2; S is area of the working (imposed by the breakdown of the test material) surfaces of the plate, m^2; b is thickness of the test material, mm; D is plate diameter (or the size of the smallest side of a rectangular plate), m^2; ΔT_1 and ΔT_2 are the temperature differences between the plate and the surrounding air, respectively, at time t$_1$ and t$_2$, K; $\tau = t_2 - t_1$ is cooling time of the plate, s.

1. Let Find estimates of the variance of the main quantities included in the calculation equation for the total thermal resistance of materials [15-16]

$$S_Q^2 = \sum_{j=1}^{m} E_j^2 = \sum_{j=1}^{m} \left(\frac{\partial F}{\partial Q_j}\right)^2 S_{Q_1}^2 \quad (4)$$

According to equation (4), the variance estimate for RΣ is calculated as follows:

$$S_R^2 = \left(\frac{\partial R}{\partial E}\right)^2 S_E^2 + \left(\frac{\partial R}{\partial \Phi}\right)^2 S_\Phi^2 + \left(\frac{\partial R}{\partial K}\right)^2 S_K^2 + \left(\frac{\partial R}{\partial m}\right)^2 S_m^2 + \left(\frac{\partial R}{\partial B}\right)^2 S_B^2 \quad (5)$$

After some calculations of $\left(\frac{\partial R}{\partial E}\right), \left(\frac{\partial R}{\partial \Phi}\right), \left(\frac{\partial R}{\partial K}\right), \left(\frac{\partial R}{\partial m}\right), \left(\frac{\partial R}{\partial B}\right)$ the equation (5) will have the following form:

$$S_R^2 = R^2 \left\{ \frac{1}{(m - BE)^2} \left[m^2 \frac{S_E^2}{E^2} + m^2 \frac{S_m^2}{m^2} + (BE)^2 \frac{S_B^2}{B^2} \right] + \frac{S_\Phi^2}{\Phi^2} + \frac{S_K^2}{K^2} \right\} \quad (6)$$

As can be seen from equation (6), the estimate of the dispersion of the total thermal resistance is determined by the estimates of the dispersion of the coefficient E, the mass of the plate m, the correction for the heat flow scattering in the device B, the device factor f, and the coefficient that takes into account the heat flow scattering in the sample K.

All these values must be calculated separately.

2. Let calculate the variance estimate of the coefficient E, which is calculated by the equation

$$E = \frac{3C_1}{3C_1 + C_2} \quad (7)$$

where C_1 is the total heat capacity of the plate, j/0C; C_2 is specific heat of the sample; $C_1 = C_n \cdot m_3$, $C_2 = 1{,}675 \cdot 10^3 \cdot M(d/d_2)^2$.

Thus, the equation for estimating the variance of the coefficient ***E*** will be in the following form:

$$S_E^2 = \frac{E^4 D^2}{9C_n^2 m_3^2} \left(\frac{1}{C_n} S_{C_n}^2 + \frac{1}{m_3} S_{m_3}^2 + \frac{1}{M} S_M^2 + \frac{4}{d^2} S_d^2 + \frac{4}{d_2^2} S_{d_2}^2 \right) \quad (8)$$

where $D = 1{,}675 \cdot 10^3 \cdot M(d/d_2)^2$.

So the estimate of the variance of the coefficient E depends on estimates of variance specific heat capacity C_n of the plate, weight plate m_3, mass of the sample M, the length of the plate d, and sample length d_2.

The variance estimate of C_2 is defined as

$$S_{C_2}^2 = C_2^2 \left(\frac{1}{M^2} S_M^2 + \frac{4}{d^2} S_d^2 + \frac{4}{d_2^2} S_{d_2}^2 \right) \quad (9)$$

This shows that the estimate of the dispersion of the total heat capacity of the sample is determined by the estimates of the dispersion of the sample mass, plate length, and sample length.

3. The cooling Rate *m*, s^{-1}, according to GOST 20489-75 is calculated by the equation

$$m = \frac{ln\Delta T_н - ln\Delta T_к}{\tau} \quad (10)$$

where $ln\Delta T_н$ and $ln\Delta T_к$ are natural logarithms of the initial and final temperatures; τ – the average cooling time of the device plate in a given range of temperature differences, ^{0}C.

In accordance with the equation (4), we define the variance estimate *m* which is equal to

$$S_m^2 = \frac{1}{\tau^2}\left(\frac{1}{t_н^2}S_{t_н}^2 + \frac{1}{t_к^2}S_{t_к}^2 + m^2 S_\tau^2\right) \quad (11)$$

So, to compute variance estimation of the cooling rate need to know what is the variance of the initial and final temperatures and cooling time.

4. Similarly to the higher points, we find an estimate of the variance of the correction for heat flow scattering in the device *B*, which according to GOST 20489-75 is equal to

$$B = \frac{(K_1/E_1)m_1 - (K_2/E_2)m_2}{K_1 - K_2} \quad (12)$$

Then,

$$S_B^2 = \frac{1}{(K_1-K_2)}\left\{\begin{array}{c}\left[\left(\frac{K_1}{E_1}m_1 - \frac{K_1}{E_1}m_2\right)^2 + \left(\frac{m_1}{E_1}K_2 + \frac{m_2}{E_2}K_2\right)\right]S_K^2 + \\ + \left[\frac{1}{E_1^2}\left(\frac{K_1}{E_1}m_3^2\right)^2 + \frac{1}{E_2^2}\left(\frac{K_2}{E_2}m_2^2\right)^2\right]S_E^2 + \left[\left(\frac{K_1}{E_1}\right)^2 + \left(\frac{K_2}{E_2}\right)^2\right]S_m^2\end{array}\right\} \quad (13)$$

Can be seen that S_B^2 depends on S_E^2, S_K^2 and S_m^2.

We have already determined S_E^2 and S_m^2 in this case, we will find S_m^2, that is, an estimate of the variance of the coefficient *K*.

5. Coefficient *K* according to GOST 20489-75 is calculated by the equation:

$$K = 0{,}4 + \frac{0{,}6}{(1+2b/d)} \quad (14)$$

where *d* is the diameter of the device plate, mm; *b* is the thickness, mm.

According to the equation (4) evaluation of the dispersion factor takes into account the scattering of the heat flow in the sample will be in the following form:

$$S_K^2 = \frac{5{,}76}{d^2(1+2b/d)^6}\left[S_b^2 + \left(\frac{b}{d}\right)^2 \cdot S_d^2\right] \quad (15)$$

As can be seen, the variance estimate for the *K* coefficient depends on the variance estimates for the diameter and thickness of the plate.

6. The device Factor Φ according to GOST 20489-75 is determined by the equation

$$\Phi = \frac{C}{S} = \frac{4C_p \cdot m_3}{\pi d^2} \quad (16)$$

where *C* is the total heat capacity of the plate, J/^{0}C; *S* is the area of the plate, m^2; C_p is the specific heat capacity of the plate; m_3 is the weight of the plate, kg; *d* is the diameter of the plate, m.

Based on the same equation (4), the device factor variance estimate will be:

$$S_\Phi^2 = \Phi^2\left(\frac{1}{C_p^2}S_{C_p}^2 + \frac{1}{m_3^2}S_{m_3}^2 + \frac{4}{d^2}S_d^2\right) \quad (17)$$

Thus, we have shown the definition of the variance estimate of all the necessary quantities to determine S_R^2.

Conclusion

1. A comparative analysis of the applied methods based on stationary and non-stationary heat exchange is Performed.

2. The higher accuracy of non-stationary methods based on measuring the cooling time of a heat cell with subsequent determination of the cooling rate and the total thermal resistance of the material under study is Noted.

3. A method is Proposed for estimating the variance of the main values necessary for calculating the total thermal resistance of materials.

4. The results of the study of the relationship between sources of uncertainty of the result of measuring the total thermal resistance of textile materials are Presented.

5. The Contribution of each source of uncertainty to the total standard and extended uncertainty of the textile materials resistance measurement result will be described in the next paper.

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