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Optimization of Thermal Subsystem of Thermo Transducers for Measuring the Temperature of Gas Flows

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Abstract

The error of measuring the temperature of gas flows by contact methods consists of two main components: 1) the error that occurs in the process of measuring the physical quantity into which the temperature is converted (the error of the measuring means); 2) errors arising in the process of converting the temperature into a measured physical value using a thermo transducer. This component of the error is completely thermal in nature and is determined by the conditions of the thermal balance between the studied gas flow and the thermo transducer and has the greatest impact on the overall measurement error. It is determined by the combined action of the following factors: heat transfer due to radiation to or from the thermo transducer; heat removal from thermo transducer due to thermal conductivity; by converting part of the kinetic energy of the gas flow into thermal energy in the wall layer surrounding the thermo transducer; by convective transfer of heat from the wall layer to the sensitive element of the thermo transducer. Note also that if the temperature of the gas flow is non-stationary, then due to the thermo transducer's own heat capacity, it does not have time to register the time-varying temperature of the flow. Due to this, a dynamic component of the measurement error arises during the measurement of non-stationary temperatures. The article investigates the component error determined by the conditions of heat exchange between the gas flow and the thermo transducer.

Keywords: temperature; gas flow; measurement error; thermo transducer; optimization.

1. Definition of the scientific problem chosen for research

The main thermal influence on the thermo transducer during measurement is the gas flow, the temperature of which must be measured. The tasks that must be solved in the process of designing a thermo transducer consist of creating such conditions in it, under which the effect of all types of thermal effects on the sensitive element of the thermo transducer, except for the main one, can be neglected. To solve such a problem, it is necessary to analyze each component of heat exchange and determine the conditions under which component errors from this type of heat exchange would be minimal. After such an analysis, during the construction of the thermo transducer, it is necessary to fully use all the possibilities of reducing each component error.

2. Analysis of recent publications and studies related to this problem

It is practically impossible to study the cumulative effect of all thermal factors on thermo transducer, since their theoretical assessment in most cases is only approximate, and some can only be determined experimentally. Therefore, for the analysis of all components of the error, the thermo transducer for measuring the temperature of gas flows is presented in the form of three serially connected subsystems: gas dynamic, thermal and electrical [1]-[4]. Such a representation makes it possible to optimize the error components of each subsystem, and to determine the

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total measurement error as a superposition of these components. The gas dynamic subsystem converts the temperature of the gas flow entering the thermo transducer into the braking temperature at the entrance to the thermo transducers braking chamber. The optimization of the gas-dynamic subsystem and the error component arising in it are studied in detail in [4]. The thermal subsystem converts the braking temperature into the temperature of the sensitive element and is characterized by components of error from heat exchange due to thermal conductivity in the design elements of the thermo transducer, heat exchange by radiation in the braking chamber, and convective heat exchange with the gas flow [5]. The electrical subsystem converts this temperature into an output signal recorded by a measuring device. It should be noted that the measurement of the temperature of gas flows is classified as a special measurement and therefore there is not a large number of publications on this subject.

3. Formulation of the purpose of the article

The purpose of the study is to optimize the thermal subsystem to minimize the error components arising from the heat exchange conditions between the studied gas flow and the thermo transducer.

To achieve this goal, it is necessary to carry out theoretical and experimental studies of the components of the measurement error of the gas flow temperature due to heat transfer associated with heat conduction in the design elements of the thermo transducer, heat exchange by radiation in the braking chamber and convective heat exchange with the gas flow, and to analyze the algorithm for their minimization during the development of the thermo transducer design.

4. Presentation and discussion of research results

The heat exchange of thermo transducers intended for measuring the temperature of gas flows is caused by heat exchange due to the thermal conductivity of the sensitive element with the design elements of the thermo transducer, heat exchange due to radiation with the inner surface of the braking chamber of the thermo transducer and convective heat exchange with the examined gas flow. It should be noted that individual dependencies, which describe the influence of factors on heat exchange conditions, are approximate in nature. Therefore, an analytical study of the cumulative effect of the main factors on the overall measurement error is impossible from a practical point of view. Based on the above, we will analyze each component of the error separately with the assumption that the remaining components are absent. In this case, the total measurement error can be interpreted as a superposition of component errors.

4.1. Mathematical model of thermal subsystem

The mathematical model of the thermal subsystem corresponds to the mathematical model of the heat exchange of the sensitive element, which should be composed taking into account its thermal interaction with the design elements of the thermo transducer, surrounding objects and gas flow, as well as the possible presence of internal heat sources.

When developing a mathematical model of the thermal subsystem of the thermo transducer, it can be considered as a homogeneous isotropic body. For such conditions, the mathematical model of heat transfer can be presented in the form of the Fourier equation of unsteady thermal conductivity [6]:

$$C_V(T)\,\frac{\partial T}{\partial \tau} = \operatorname{div}[\lambda(T)\,\operatorname{grad}(T)] + \omega, \tag{1}$$

where C_v, λ is the volumetric heat capacity and thermal conductivity of the materials of the sensitive element, respectively; *div* and *grad* are divergence and gradient operations; ω is distribution function of energy sources over the volume of the thermo transducer.

For certain defined temperature intervals ΔT, it can be assumed that for a specific material the coefficients $C_V(T)$ and $\lambda(T)$ are independent of temperature. Then equation (1) will become linear and take the form:

$$\frac{\partial T}{\partial \tau} = a\,\operatorname{div}(\operatorname{grad} T) + \frac{1}{C_V}\,\omega, \tag{2}$$

where a is the coefficient of thermal conductivity of the material of the sensitive element.

Equation (2) is a generalized mathematical model of the thermal subsystem of the thermo transducer. As indicated above, the heat exchange of the thermo transducer for measuring the temperature of gas flows is due to heat exchange through the thermal conductivity of the sensitive element with the structural elements of the thermo transducer, radiation heat exchange with the inner surface of the braking chamber and convective heat exchange with the gas flow. Let's consider methods of influence on component errors caused by each of components of heat exchange.

4.2. Error component due to heat transfer associated with thermal conductivity

When measuring the temperature of gas flows, thermo transducers must be fixed in a certain way in some fittings (pipelines, tanks, etc.), the temperature of which, in general, differs from the temperature of the gas flow. As a result, the temperature distribution along the length of the thermo transducer will be uneven. Due to heat dissipation through the thermo transducer housing and connecting or thermoelectrode conductors, the temperature of the sensitive element t_{se} will differ from the actual temperature of the gas flow t_0.

Quantitative assessment of this phenomenon can be obtained from the analysis of the heat balance of the thermo transducer when only the convective heat flow acts on the sensitive element and the heat is removed to the place of attachment. The influence of heat removal on the temperature of the sensitive element of the thermo transducer can be considered as a process of heat exchange between the gas flow and the thermo transducer, made in the form of a homogeneous rod, which is fixed on the wall of the armature with a temperature of t_w.

When building a mathematical model, we make the following assumptions:

- the thermal effect of the sensitive element on the design elements of the thermo transducer is not taken into account;
- the thermal contact of the end surface of the sensitive element with the fastening elements is absolute, that is, there is no thermal resistance;
- the temperature change of the thermo transducer (rod) $t(x)$ in the radial direction is not taken into account, but remains constant only along its axis and in each cross section.

The heat exchange equation for such thermo transducer is:

$$\frac{d^2 t_t(x)}{dx^2} - \nu^2[t_0 - t_t(x)] = 0, \tag{3}$$

where $\nu^2 = \alpha U/(\lambda S)$; α is full coefficient of heat exchange between thermo transducer and flow; U and S are the perimeter and cross-sectional area of the thermo transducer, respectively; λ is the coefficient of thermal conductivity of the thermo transducer material.

We assume that the heat entering through the end of the thermo transducer at x=0 can be neglected in comparison with the heat entering through its side surface and that the temperature of the thermo transducer at $x=L$ is equal to the temperature of the wall t_w:

$$\frac{dt_t(x)}{dx} = 0 \text{ at } x=0; \;\; t = t_w \text{ at } \; x = L. \tag{4}$$

Assuming that the coefficient ν does not depend on the temperature of the flow and the coordinate x, taking into account (4) we obtain:

$$\frac{t_0 - t_t(x)}{t_0 - t_w} = \frac{\mathrm{ch}(\nu_x)}{\mathrm{ch}(\nu_L)}. \tag{5}$$

The component of the measurement error Δt_c due to heat removal associated with thermal conductivity when placing a sensitive thermo transducer element at the point x=0 (for example, a thermocouple junction) will be determined by the following dependence:

$$\Delta t_c = t_t - t_0 = -\frac{t_0 - t_w}{ch\mu}, \tag{6}$$

where
$$\mu = \nu L = L\sqrt{\frac{\alpha U}{\lambda S}}. \tag{7}$$

Expressing U and S in terms of the thermo transducer diameter d, we obtain:

$$\Delta t_c = t_t - t_0 = -\frac{t_0 - t_w}{\mathrm{ch}(L)\sqrt{\frac{4\alpha}{d\lambda}}}. \tag{8}$$

Equation (8) is the starting point for estimating the component error of gas flow temperature measurement from heat exchange due to thermal conductivity.

4.3. Methods of influence on the error component due to heat exchange associated with thermal conductivity

It can be seen from equation (8) that the value of this error component can be reduced in the following ways:

- by reducing the temperature difference ($t_0 - t_w$);
- by increasing the immersion depth L of thermo transducer in the gas flow;
- reducing the diameter of thermo transducer, thermoelectrode and connecting conductors, as well as choosing them with low thermal conductivity;
- by increasing the coefficient of convective heat transfer from the gas flow to the sensitive thermo transducer element.

It is practically difficult to reduce the temperature difference ($t_0 - t_w$). Basically, this can be achieved only due to electric heating of the wall on which the thermo transducer is fixed. Such a measure makes it possible to almost completely eliminate the error component from heat exchange due to thermal conductivity, but it is associated with great operational difficulties.

The temperature t_w is determined by the interaction of the protruding part of the thermo transducer with the external environment in which it is installed. Since the temperature t_w depends on the intensity of heat exchange of the protruding part of the thermo transducer, located outside the gas flow, with the environment, it is necessary to design the protruding part as small as possible and heat-insulate it from the environment. Such thermal insulation can be achieved by placing between the wall and the thermo transducer body gaskets made of material with low thermal conductivity (for example, textolite, glass textolite, asbestos cement, etc.) or by placing non-thermally conductive screens around the protruding part of the thermo transducer.

The immersion depth L of the thermo transducer in the gas flow can be changed most freely. This depth of immersion should be as large as possible. But even with a large depth of immersion of the thermo transducer, the temperature of the protective case will differ slightly from the temperature of the gas flow due to the influence of radiation and the conversion of part of the kinetic energy into thermal energy. That is, by changing the immersion depth of the thermo transducer, you can only weaken the heat dissipation through the case.

Let's consider the influence of the depth of immersion on the readings of the thermo transducer, the design of which is schematically shown in Fig.1,*a*. The housing of the thermo transducer is made of stainless steel of the 12X18H10T brand, for which the coefficient of thermal conductivity λ=26 W/(m·K). The immersion depth was L_1= 100 mm and L_2= 20 mm. A thermocouple with a nominal static characteristic of type K according to [7] served as a sensitive element. At L_1 = 100 mm, the error from heat dissipation along the body for the temperature of the gas medium t = 1000 °C was ≈3%, and at L_2 = 20 mm, this error increased to ≈ 7% (Fig.1,*b*).

To reduce the error, it is advisable to use thermal electrodes with low thermal conductivity. This makes it possible to produce thermo transducer of any design rather compactly. This especially applies to thermo transducers with a longitudinal flow around the sensitive element, since it is more difficult for them to provide a sufficient depth of immersion that would guarantee minimal errors from heat removal due to thermal conductivity.

During the flow of a gas stream around a solid body, a wall layer is formed near its surface, within which the velocity of the medium decreases from a value equal to the velocity of the oncoming stream to zero. The amount of heat transferred from the medium to the solid body will be determined by the convective heat transfer coefficient α, which depends on the Reynolds criterion, the geometric parameters of the thermo transducer and the parameters of the gas flow.

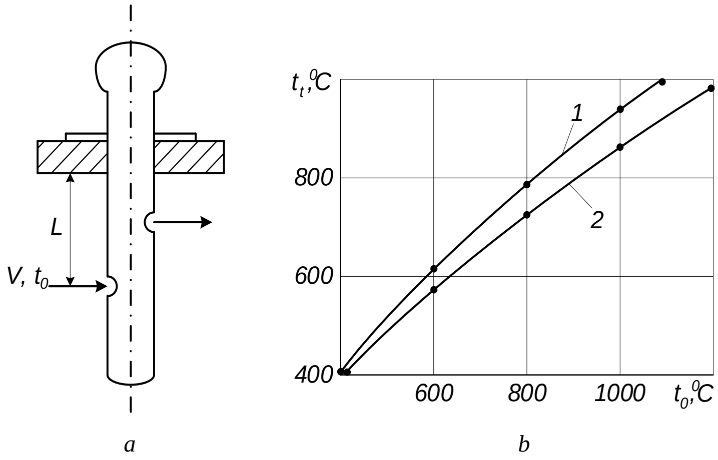

Fig.1. Calculation scheme (*a*) and dependence (*b*) of thermo transducer readings on flow temperature for different immersion depths: 1 – *L*=100 mm; 2 – *L*=20mm.

According to the results of many studies [2], [8] and according to the authors' research, at subsonic flow velocities in the range of *Re* change from 100 to 10,000, the following empirical dependencies characterizing the heat exchange between the thermo transducer and the gas flow can be recommended:

- for round cylindrical thermo transducers that are transversely washed by the flow

$$Nu = (0.44 \pm 0.06)Re^{0.5}, \tag{9}$$

- and for longitudinal flow

$$Nu = (0.085 \pm 0.009)Re^{0.674}. \tag{10}$$

Dependencies (9) and (10) cover the temperature range from 15 to 1620 °C and Mach numbers M from 0.015 to 0.9. These data can be used during the synthesis of thermo transducer with braking chambers, in which the gas flow rate always corresponds to the number $M<1$.

The value of the heat transfer coefficient α can be adjusted by changing the diameter of the thermo transducer and the flow rate inside the braking chamber. But the coefficient α can vary within relatively small limits, since a decrease in the diameter of the thermo transducer leads to a decrease in its mechanical strength, and an increase in the speed in the braking chamber will lead to an increase in the speed error due to the incomplete conversion of the kinetic energy of the moving gas into thermal energy in the wall layer surrounding the sensitive element of the thermo transducer, which is the main one for the gas dynamic subsystem of thermo transducer [4]. So, there is a certain optimum for the resulting action of the specified factors.

The results of theoretical calculations show that with a decrease in the Reynolds number (and, accordingly, with a decrease in the intensity of convective heat exchange), it is necessary to increase the depth of immersion of the thermo transducer in the gas flow. The recommended ratio L/d can be in the range from 20 to 50 and is sufficient to almost completely eliminate the error from heat dissipation.

Typical designs of thermo transducer for reducing the heat dissipation from the sensitive element are shown in Fig.2. In the thermo transducer shown in Fig.2,*a* the length of the working part is equal to 50 diameters of the thermoelectrodes, which ensures the weakening of heat dissipation from the case.

The presence of holes with a sufficiently large distance from the junction of the sensitive element in the thermo transducer shown in Fig.2,*b*, increases the conditional depth of immersion, which is especially important in conditions of limited working space for installation of thermo transducer. As a rule, such a thermo transducer is suitable for operation only in the absence of heat exchange by radiation, since its design does not provide for shielding. In the thermo transducer of this design, the error from heat dissipation is reduced due to the fact that the gas flow moves around the thermoelectrodes of the thermocouple over a sufficiently large gap from the junction to the output holes.

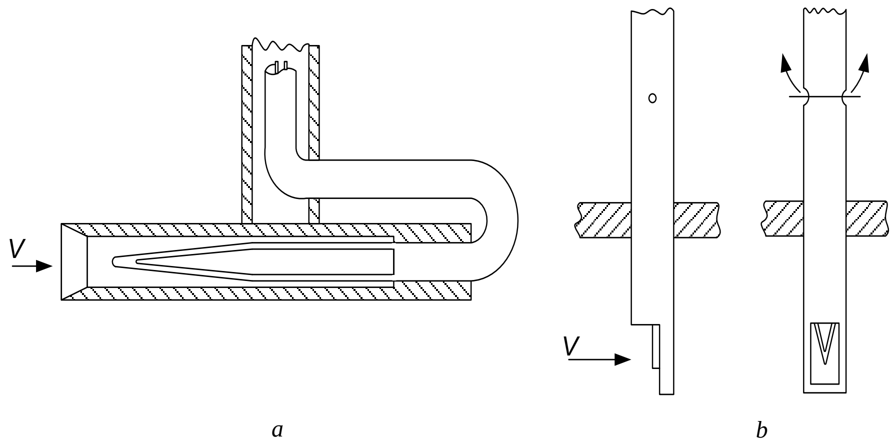

Fig.2. Typical designs of thermo transducer for reducing heat dissipation due to thermal conductivity.

4.4. Error component due to heat exchange from radiation

During the analysis of heat exchange due to radiation, it was assumed that only two types of heat exchange (i.e. convective and radiation) take part in the heat balance of the thermo transducer.

When the gas stream flows around the sensitive element of the thermo transducer due to convective heat transfer from the stream to the surface, it receives the amount of heat Q_1 per unit of time, which is determined by the expression:

$$Q_1 = \alpha F_t (t_0 - t_t), \tag{11}$$

where F_t is the surface area of the thermo transducer part immersed in the gas flow.

This effect of gas flow on thermo transducer is a beneficial effect.

The value of the heat flow Q_2, which is given off by the surface of the immersed part of the thermo transducer by radiation heat exchange with the surfaces of the walls surrounding the flow, is determined by the dependence:

$$Q_2 = \frac{\sigma \varepsilon_t F_t}{\xi}\left[\left(\frac{T_t}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4\right], \tag{12}$$

where σ is Stefan-Boltzmann constant; ε_t is total coefficient of blackness of the thermo transducer surface; ξ is the coefficient of reduction of heat losses by radiation due to gas flow around the thermo transducer; T_t , T_w are respectively, the thermodynamic temperatures of the sensitive element of thermo transducer and the surrounding walls.

Solving equations (11) and (12) assuming that there are no heat losses due to reasons other than radiation, we obtain the dependence for determining the component error due to radiation:

$$\Delta t_r = t_t - t_0 = \frac{\sigma \varepsilon_\text{п}}{\alpha \xi}\left[\left(\frac{T_t}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4\right]. \tag{13}$$

4.5. Methods of influence on the error component due to heat exchange due to radiation

It can be seen from equation (13) that the component of the error due to radiation can be optimized by changing three parameters: the total blackness coefficient ε_t, the convective heat transfer coefficient $\alpha$and the temperature of the surrounding walls T_w.

To reduce the component error Δt_r, it is advisable to use thermoelectrode and structural materials with a low and stable blackness coefficient under different external conditions. But in these conditions, the designer is very limited in his choice, since there are other no less important requirements for thermoelectrode and construction materials (sensitivity, refractory, elasticity, etc.), which are not always consistent with the requirement of a low and stable value of the blackness coefficient. However, even in these cases, the radiation error can be reduced by coating the base material with metals with a low blackness coefficient, such as silver (0.05), gold (0.05), or platinum (0.18). It is shown in [5] that when using such coatings, the error due to radiation can be only 13% of the error that occurs for similar conditions in a structure without a coating. The disadvantages of coatings include the fact that they break down over time and lose their effectiveness.

As for the increase in the convective heat transfer coefficient α, all the judgments given above are valid here, according to which the heat transfer coefficient can vary within relatively small limits.

The main means of influencing the error component caused by radiation is an increase in the temperature of the wall t_w. When the temperatures of the gas flow and the walls are equal, losses due to radiation are completely excluded. However, it is very difficult to practically implement this condition. To reduce the difference between the temperature of the walls and the temperature of the gas flow, thermal insulation of the walls is sometimes used, but most often the reduction of the influence of cold walls is achieved by effective shielding of the sensitive element with one or more screens. Protective screens must be installed between the sensitive element of the thermo transducer and the walls. A sensitive element protected by a screen will lose less heat than without a screen and its temperature will be closer to the temperature of the gas flow. If there are cold walls, the screen participates in radiation heat exchange with them, and the sensitive thermo transducer element interacts with the screen.

The summary of heat transfer by radiation in shielded thermo transducers with longitudinal and transverse gas flow, the issue of calculating the number of screens necessary so that the radiation error component does not exceed the specified value, as well as precautions that must be taken into account during the design of shielded thermo transducers are described in detail in [5].

It should be noted that not all complications created by radiation exposure can be eliminated by only installing additional screens. If the gas flow rate is very low or if there are rather strict requirements for measurement accuracy, then the number of necessary screens will increase significantly, the design of the thermo transducer will become cumbersome and in most cases it will be practically impossible to implement. In such cases, it is possible to recommend the use of electric heating of the internal screen or to increase the flow rate of the gas flow inside the thermo transducer between the screens using external devices (suction pyrometers). But when using external suction, it is necessary to consider the possible increase in speed error.

5. Conclusion

The analysis of the mathematical model of the thermal subsystem of the thermo transducer for measuring the temperature of gas flows shows that the heat exchange in the subsystem is carried out through the thermal conductivity of the sensitive element with the structural elements of the thermo transducer, radiation with the inner surface of the braking chamber and convective heat exchange with the gas flow. The article describes the methods of influencing the component errors caused by each component of heat exchange. To reduce the component error due to heat exchange associated with thermal conductivity, it is advisable to use the following methods: reduce the difference between the temperatures of the gas flow and the surrounding walls, in which the thermo transducer is placed; increase the depth of immersion of the thermo transducer in the gas stream; reduce the diameter of thermo transducer, thermoelectrode and connecting conductors, as well as choose them with low thermal conductivity; to increase the coefficient of convective heat transfer from the gas flow to the sensitive element of the thermo transducer. The reduction of the component error due to heat exchange due to radiation is carried out by changing the total blackness coefficient, the convective heat transfer coefficient and the temperature of the surrounding walls.

References

[1] V.O. Fedynets, J.P. Yusyk, I.S. Vasylkivskyi. (2019) Analysis of temperature measurement errors by contact thermo transducers // *Materials of the VI International scientific and technical Internet conference "Modern methods, information, software and technical support of management systems of organizational, technical and technological complexes"*, November 20, 2019 [Electronic resource] - K: NUHT ,.- p.278. Access mode: http://nuft.edu.ua/page/view/konferentsii ISBN 978-966-612-234-9.

[2] Moffat R. J. (1962) Gas Temperature Measurement // *“Temperature, Its Measurement and Control in Science and Industry”*, Vol.III, Part 2. -N.Y.: Reinhold Publ. Corp, 1962. – 321 p.

[3] Lutsyk, Ya. T., Huk, O. P., Lakh, O. I., & Stadnyk, B. I. (2006). Temperature measurement: theory and practice. Lviv: Beskyd Bit Publishers, 2006.- 560 p. (in Ukrainian).

[4] V. Fedynets, I. Vasylkivskyi, Y. Yusyk. Optimization of gas dynamical subsystem of transducers for measurement of gas flow temperature. *Energy Engineering End Control System*, V.2, No.2, 2016, p. 43–48.

[5] E.P. Pistun, V.O. Fedynets. (2010)/ Minimization of the component error from heat exchange due to radiation during temperature measurement of gas flows // "*Metrology and devices*" No. 6, 2010. - p. 34-37. (in Ukrainian).

[6] Yaryshev N. A. Theoretical principles of measurement of non-stationary temperatures. Energoatomizdat. L., 1990, 254 p. (in Russian).

[7] Thermoelectric temperature transducers. Part 1. Performance specification and tolerance of the electromotive force (EMF): DSTU EN 60584-1:2016 (EN 60584-1:2013, Idt). – [Effective 2016–11–01]. – Kyiv: State Committee of Ukraine for Technical Regulation and Consumer Policy, 2016. – 90 p. - (National Standards of Ukraine). (in Ukrainian)

[8] Tsyryulnikov, I.S., Komarov, V.I., Maslov, A.A. Measurement of the gas flow stagnation temperature by the method of two identical thermocouples in the short-duration aerodynamic facilities // *Flow Measurement and Instrumentation*, 2021, V. 77 article number 101863, DOI: 10.1016/j.flowmeasinst.2020.101863.

Оптимізація теплової підсистеми термоперетворювачів для вимірювання температури газових потоків

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Анотація

Похибка вимірювання температури газових потоків контактними методами складається із двох основних складових: 1) похибки, що виникає в процесі вимірювання фізичної величини, в яку перетворена температура (похибка засобів вимірювання); 2) похибки, що виникає в процесі перетворення температури у вимірювану фізичну величину з допомогою термоперетворювача (ТП). Ця складова похибки має повністю тепловий характер і визначається умовами теплового балансу між досліджуваним газовим потоком і ТП та має найбільший вплив на загальну похибку вимірювання. Вона визначається сукупною дією таких чинників: тепловіддачею через випромінення до термоперетворювача або від нього; тепловідведенням від термоперетворювача за рахунок теплопровідності; перетворенням частини кінетичної енергії газового потоку в теплову в пристінному шарі, що оточує термоперетворювач; конвективним перенесенням тепла із пристінного шару до чутливого елемента термоперетворювача. Відмітимо також, що якщо температура газового потоку є нестаціонарною, то за рахунок власної теплоємності термоперетворювача він не встигає реєструвати змінну в часі температуру потоку. За рахунок цього під час вимірювання нестаціонарних температур виникає динамічна складова похибки вимірювання. В статті проведено дослідження складової похибки, що визначається умовами теплообміну між газовим потоком і термоперетворювачем.

Ключові слова: температура; газовий потік; похибка вимірювання; термоперетворювач; оптимізація.