Volume 10, Number 2, 2024 96

Research of Thermal Inertia of Thermotransducers for Measuring the Temperature of Gas Flows

Vasyl Fedynets*, Ihor Vasylkivskyi

Lviv Polytechnic National University, 12 S. Bandery St., Lviv, 79013, Ukraine

Received: October 15, 2024. Revised: November 07, 2024. Accepted: November 14, 2024.

Abstract

The temperature of gas flows is an important parameter during the research of heat and mass transfer processes, in the field of gas dynamics, as well as in manufacturing. Therefore, it is necessary to ensure a high level of requirements for the accuracy and reliability of the primary means of temperature measurement. The basic requirements are the simplicity of the design of the thermotransducer, its low thermal inertia, small dimensions, and high reliability during operation in aggressive environments at high temperature and pressure conditions. When measuring the temperature of gas flows, an important requirement is to ensure low thermal inertia. The presence of thermal inertia in thermotransducers leads to the fact that during the measurement of non-stationary temperatures of gas flows in conditions of variable heat transfer, dynamic errors occur, which make it necessary to conduct additional studies to take them into account. This paper provides a study of the thermal inertia of thermotransducers for measuring the temperature of gas flows depending on the type of flow temperature change.

Keywords: thermotransducer; methodology; gas flow; measurements; temperature; time of thermal reaction.

1. Introduction

Due to a certain value of the heat capacity of the sensitive element (SE) of thermotransducer (TT), its temperature will always lag behind the temperature of the gas flow, if this temperature has changed. When measuring the time-varying temperature, the TT also does not have time to follow the temperature change, as it takes some time. Distortions of TT readings due to non-stationarity both in the TT itself and between the TT and the environment are caused by thermal inertia. A quantitative indicator of inertial properties is the thermal reaction time ε, which, according to standards [1]-[3], is defined as the time required to change the readings of the device by a certain percentage with a gradual change in the temperature of the environment.

As a result of thermal inertia, there is an additional difference between the temperatures of the fuel cell and the gas flow, which determines the dynamic (inertial) error in the measurement of the temperature of the gas flow.

The dynamic error can be determined by evaluating the heat exchange conditions of the TT with the flow and the walls surrounding it, as well as the heat capacity of the SE. Many factors can simultaneously affect the heat exchange of the TT. Some of them are beneficial and then the TT will receive heat from the gas flow. When exposed to negative influences, the TT can receive or give off heat through interaction with the environment or other heat sources. Therefore, the solution of the heat balance equation of the TT with the simultaneous effect on it of both beneficial and harmful influences becomes much more complicated.

* Corresponding author. Email address: vasyl.o.fedynets@lpnu.ua

This paper should be cited as: V. Fedynets, I. Vasylkivskyi. Research of thermal inertia of thermotransducers for measuring the temperature of gas flows. *Energy Engineering and Control Systems*, 2024, Vol. 10, No. 2, pp. 96 – 101. https://doi.org/10.23939/jeecs2024.02.096

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

For contact TTs, with the help of heat transfer laws, it is possible to calculate errors arising because of heat exchange between the studied gas flow and the TT and find ways to eliminate them. Heat transfer also has a significant impact on the dynamic characteristics of TT. Analytical dependencies for determining thermal inertia and dynamic errors of gas flow temperature measurement are derived based on the theory of regular thermal regime [4], [5]. It should be noted that measuring the temperature of gas flows is a special measurement method, so there is a limited number of publications on these issues. The main ones include research in publications [6], [7].

3. Formulation of the goal of research

The purpose of this work is to study the influence of various thermal factors on the thermal inertia of the TT for measuring the temperature of gas flows.

To achieve this goal, it is necessary to investigate the effect on the thermal inertia of the following thermal interactions: simple heating or cooling, heating or cooling under the conditions of a linear temperature change, and heat exchange with harmonic changes in the gas flow temperature.

4. Presentation and discussion of research results

To simplify the description of the heat exchange conditions, we consider that there is one beneficial and one negative effect on the TT, we assume that the TT are bodies of the simplest geometric shapes, and we consider the thermophysical properties of the SE to be constant and independent of temperature, it is possible due to the influence of thermal conductivity and radiation. In addition, assume that the characteristics of the thermal interaction of SE with the environment and other bodies are constant and do not depend on temperature.

In practice, the following beneficial effects are most often noted:

- simple heating or cooling in a gas stream with a constant temperature;
- heating or cooling in the conditions of a change in flow temperature according to a linear law;
- heat exchange with harmonic changes in flow temperature.

With a gradual change in the temperature of the flow t_0 SE during a time interval $d\tau$ receives a certain amount of heat dQ:

$$dQ = \alpha F(t_0 - t_s)d\tau, \tag{1}$$

where α is the coefficient of convective heat transfer from the gas flow to the TT; F is surface area of the SE; t_s is the temperature of the sensitive element.

This amount of heat will cause the temperature t_s to rise.

$$dQ = CMdt_s, \tag{2}$$

where C and M are the heat capacity of the material and the mass of the SE, respectively.

Based on (1) and (2), we obtain:

$$\frac{dt_s}{d\tau} + m(t_s - t_0) = 0, \tag{3}$$

where $m = \alpha F/(CM) = \alpha F/(C\rho V)$; ρ is density of the material of SE; V is volume of SE.

The following assumptions are taken:

- SE is a body in which, with a change in the temperature of the flow, the temperature throughout the volume simultaneously changes and its uniform distribution at all points of the SE is not disturbed;
- the coefficient of convective heat transfer from the flow to the heat exchanger during the temperature change remains constant;
- the heat capacity of SE does not change over time and does not depend on temperature;

• thermal influence occurs only from the flow to the SE, then the parameter m will be a constant value.

The value inverted to m determines the thermal reaction time ε:

$$\varepsilon = \frac{1}{m} = \frac{CM}{\alpha F} = \frac{C\rho V}{\alpha F}. \tag{4}$$

From (4), for a cylindrical SE $\varepsilon = C\rho d/4\alpha$, and for a spherical one $\varepsilon = C\rho d/6\alpha$ (d is the diameter of the SE).

Expressions (3) and (4) show that the time of the thermal reaction ε depends on the geometric shape and dimensions of the sensitive element, the heat capacity and density of the material from which the sensitive element is made, as well as the coefficient of convective heat transfer between the gas flow and the sensitive element.

Let us represent the temperature of the gas flow t_0 by a function of time $f(\tau)$. Under initial conditions $t_0|\tau = \tau_0 = f(\tau_0) = t_0'$; $t_s|\tau = \tau_0 = t_p$ solution of the linear differential equation (3) will have the form:

$$t_s = t_0 \left(t_{\mathrm{p}} - t_0'\right)e^{-m(\tau-\tau_0)} - e^{-m\tau}\int_{\tau_1}^{\tau_2} e^{m\tau} f'(\tau)\, d\tau. \tag{5}$$

The dynamic or inertial error Δt_d is expressed as a dependence:

$$\Delta t_d = t_s - t_0 = \left(t_{\mathrm{p}} - t_0'\right)e^{-m(\tau-\tau_0)} - e^{-m\tau}\int_{\tau_1}^{\tau_2} e^{m\tau} f'(\tau)\, d\tau. \tag{6}$$

For the case of simple heating or cooling in the gas flow with $f(\tau)$ = const and $f'(\tau) = 0$ (step temperature change from t_p до t_0), expression (6) will have the form

$$\Delta t_d = t_s - t_0 = -\left(t_0 - t_p\right)e^{-m(\tau-\tau_0)} = -\left(t_0 - t_p\right)e^{-\frac{\tau-\tau_0}{\varepsilon}} \tag{7}$$

and the equation of the dependence of SE readings t_s on the heating time will have the form

$$t_s - t_p = \left(t_0 - t_p\right)\left[1 - e^{-m(\tau-\tau_0)}\right] = \left(t_0 - t_p\right)\left(1 - e^{-\frac{\tau-\tau_0}{\varepsilon}}\right). \tag{8}$$

Equations (7) and (8) are called transitional functions of TT.

With a linear change in time of the temperature of the gas flow according to the law

$$t_0 = t'_0 + A\tau, \tag{9}$$

the temperature of SE will change according to the following law:

$$t_s = t'_0 + A(\tau - \varepsilon) + \left(t_{\mathrm{p}} - t'_0 + A\varepsilon\right)e^{-\frac{\tau}{\varepsilon}}. \tag{10}$$

If $\tau \to \infty$, then:

$$t_s \approx t'_0 + A(\tau - \varepsilon). \tag{11}$$

So, the temperature of the SE changes according to the same law as the temperature of the gas flow, but with a time delay of ε.

Fig.1 shows the response of a sensitive TT element with different values to a gradual change in flow temperature.

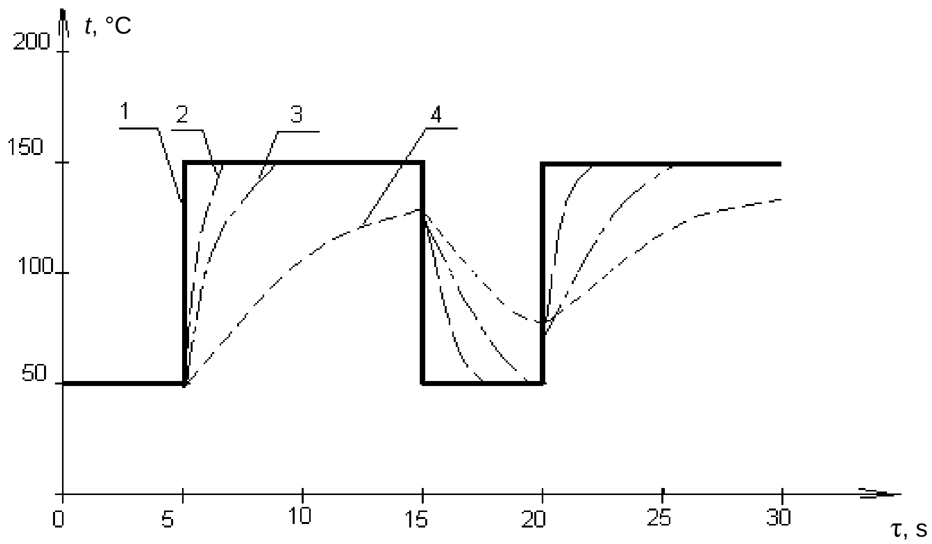

Fig.1. The reaction of the sensitive element of the TP to the gradual change in the temperature of the gas flow at different values of the thermal reaction time: 1 – the law of the change in the temperature of the flow; 2 – ε = 0.05 s; 3 – ε = 0.5 s; 4 – ε =2.5 s.

The response of the sensitive TT element to the linear change in flow temperature at different values is shown in Fig.2.

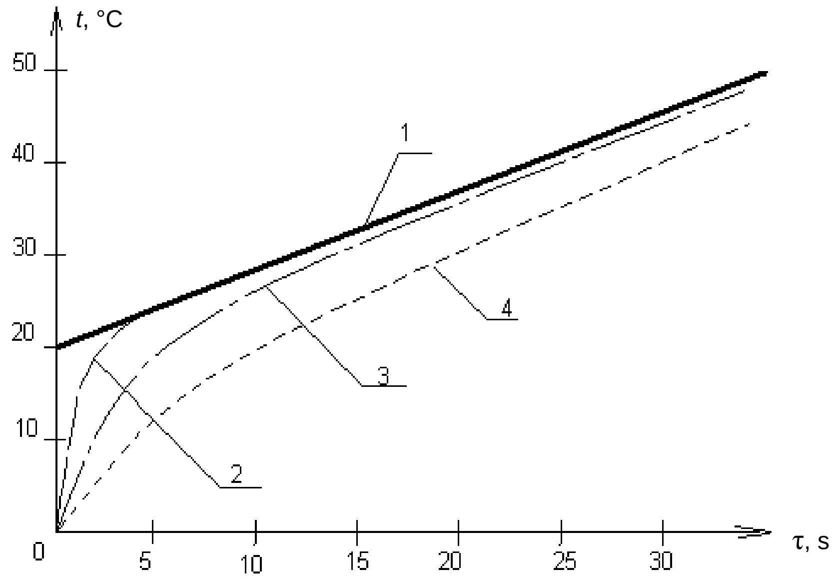

Fig.2. The reaction of the sensitive element of the TP to the linear change in the gas flow temperature at different values of the thermal reaction time: 1 – the law of the flow temperature change; 2 – ε = 0.05 s; 3 – ε = 0.5 s; 4 – ε =2.5 s.

With a sinusoidal change in the temperature of the gas flow according to the law

$$t_0 = t'_0 + t_A \sin \omega \tau, \tag{12}$$

the temperature of the SE changes according to the following law:

$$t_s = t'_0 + \frac{t_A}{R}[sin(\omega\tau - arctg\omega\varepsilon)], \tag{13}$$

where $R = \frac{1}{\sqrt{1+\omega^2\varepsilon^2}}$ is frequency characteristic of the sensitive element, which is defined as the ratio of the amplitude of the fluctuations of the sensitive element to the amplitude of the fluctuations of the flow temperature, that is, it changes with the same frequency, but with a reduced amplitude and phase shift relative to the temperature change of the gas flow.

The influence of the thermal response time on the frequency response of the sensitive element is shown in Fig.3.

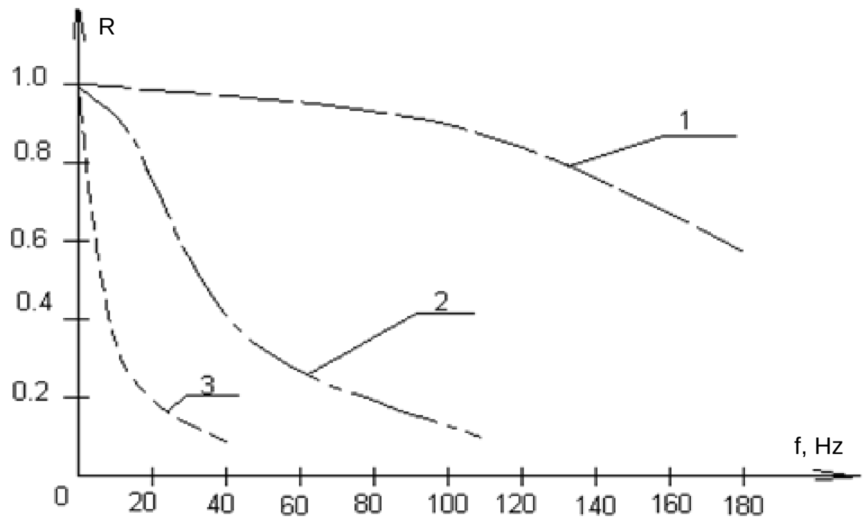

Fig.3. The influence of the time of the thermal reaction on the frequency characteristic of the sensitive element of the TT:
1 – ε = 0.05 s; 2 – ε = 0.5 s; 3 – ε =2.5 s.

To determine the dynamic error of TT, which are complex bodies or a system of bodies in expression (6), it is necessary to use the theorem on the average value. Then, under the condition that $f'(\tau) = dt_0/d\tau$ does not acquire infinite values that have no physical meaning, as the difference ($t - t_0$) decreases, the expression for the dynamic error will have the form:

$$\Delta t_d = -\varepsilon \frac{dt_0}{d\tau}. \tag{14}$$

Expression (14) shows that for TT with a given value of the thermal reaction index, the dynamic error will depend on the rate of change in the temperature of the gas flow. If the rate of change in the temperature of the gas flow is unknown, the temperature change obtained with the help of the TT, the dynamic error of which is determined, can be used to calculate the dynamic error of the TT.

Let's write down the heat balance equation for a cylindrical SE of length L for the time $\Delta\tau$ between the heat coming from the gas flow to the SE and the heat absorbed by it, under the condition of uniform temperature distribution along the cross-section and insignificant (negligible) losses due to heat removal through the output conductors:

$$\alpha(t_0 - t_s)\pi d L \Delta\tau = \frac{\pi d^2}{4} L\rho C \frac{dt_s}{d\tau}\Delta\tau. \tag{15}$$

Given that for cylindrical SE $\varepsilon = C\rho d/4\alpha$ [8] we will obtain:

$$\Delta t_d = t_s - t_0 = -\varepsilon \frac{dt_s}{d\tau}. \tag{16}$$

This dependence can be used to estimate the dynamic errors of measuring the temperature of gas flows and to determine the thermal reaction time of the TT.

The expression for the relative dynamic error can be given in the following form:

$$\delta t_d = \frac{t_0 - t_s}{t_0 - t_p} = e^{-\frac{\tau}{\varepsilon}}. \tag{17}$$

The real values of the dynamic error are determined by the thermal reaction time of the TT.

5. Conclusion

Analysis of the expression for the relative dynamic error (17) makes it possible to find some characteristic points for the process of simple heating or cooling: if $\tau = \varepsilon$, then $\delta t_d = 1/e = 0.368$; if $\tau = 0.693\varepsilon$, then $\delta t_d = 0.5$ and with $\tau = 3\varepsilon$, $\delta t_d = 0.05$. The physical value of the time of the thermal reaction is that at the moment of time $\tau = \varepsilon$ SE perceives 0.632 of the initial temperature difference between the gas flow and TT, and the difference between the temperatures of the gas flow and TT is equal to 0.368 of this difference. This value is regulated in national standards [1], [2]. In foreign countries, it is generally accepted that the TT heats up to $0.5t_0$ [3] or $0.95t_0$. The authors consider that, there is no need to strictly regulate the dynamic characteristics of TT in the standards. This will make it possible, in addition to the thermal reaction time, to present the dynamic characteristics of TT in another forms (such as transient characteristic, transfer function, etc.).

References

[1] Metrology. Resistance thermoconverters made of platinum, copper and nickel. General technical requirements and test methods : DSTU GOST 6651:2014. – K.: Ministry of Economic Development of Ukraine, 2015. - 26 p. (in Ukrainian)

[2] 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)

[3] IEC 60584-1:2013. Thermocouples – Part 1: EMF specifications and tolerance Maintenance Result Date.

[4] Bulyandra, O.F. (2006). Technical thermodynamics : textbook. Technika, 320 p. (in Ukrainian)

[5] Shinkaryk, M.M. and Kravets, O.I. (2024). Basics of heat engineering : teaching manual. Individual entrepreneur Palyanitsa V.A., 132 p. (in Ukrainian)

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

[7] Fedynets, V.O., Yusyk, J.P. and Vasylkivskyi, I.S. (2019). Peculiarities of measuring the temperature of gas flows using thermocouples. *Materials of the VII International scientific and technical Internet conference "Modern methods, information, software and technical support of management systems of organizational, technical and technological complexes"*, Kyiv, 26 November 2020. Access mode: https://nuft.edu.ua/naukova-diyalnist/naukovi-konferencii/ (in Ukrainian)

[8] Moffat, R.J. (1962). Gas Temperature Measurement; Temperatures, Its Measurement and Control in Science and Industry / Editor-in-Chief Charles M. Herzfeld, Reinhold Publishing Corporation in NY, 3(2), p.553-571.

Дослідження термічної інерційності термоперетворювачів для вимірювання температури газових потоків

Василь Фединець, Ігор Васильківський

Національний університет «Львівська політехніка», вул. С. Бандери, 12, м. Львів, Україна

Анотація

Температура газових потоків є важливим параметром під час проведення досліджень процесів тепло-масообміну, в області газової динаміки, а також і в промисловості. Тому необхідно забезпечити високий рівень вимог до точності та надійності первинних засобів вимірювання температури. Засадничими вимогами, зокрема, є простота конструкції термоперетворювача, його низька термічна інерційність, малі розміри, висока надійність під час експлуатації в агресивних середовищах при високих значеннях температури та тиску. При вимірюванні температури газових потоків важливою вимогою є забезпечення низької термічної інерційності. Наявність у термоперетворювачів термічної інерційності призводить до того, що під час вимірювання нестаціонарних температур газових потоків в умовах мінливої тепловіддачі виникають динамічні похибки, які роблять необхідним проведення додаткових досліджень для їх врахування. В статті наведено дослідження термічної інерційності термоперетворювачів для вимірювання температури газових потоків в залежності від виду форми зміни температури потоку.

Ключові слова: термоперетворювач; методика; потік газу; вимірювання; температура; час термічної реакції.