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TRANSLATION

A RADIATION THERMOMETER

By

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FOREIGN TECHNOLOGY DIVISION

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BY: I. D. Semikin

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A RADIATION THERMOMETER

by

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This article reports the description of an instrument worked out by the authors for the measurement of emission heat flows.

The instrument possesses stability of performance, high sensitivity, and other properties which favor its application in systems for the automation of commercial furnaces.

Introduction

Present-day furnaces for annealing metal (prior to rolling, forging, stamping, etc.) do have automatic control and regulation systems which facilitate the control process by the heat cycle of the furnaces. At the same time, the control process is not yet completely automated. This is so for a number of reasons, one of the primary being that in furnace automation technique, one of the most important elements--a sufficiently precise and dependable means of measuring metal temperatures in the annealing process--has not yet been developed.

Existing instruments for the measurement of high temperatures (radiation, optical, chromatic, and photo-electric pyrometers), when used under conditions of metallurgical production, only make it possible to roughly approximate the temperature of the metal being annealed. This is explained by the fact that in measuring furnace temperatures it is difficult to establish conditions under which these instruments can furnish sufficiently precise readings, i.e. conditions which prevent flares, dust, and incandescent gases from falling into the pyrometer's field of view.

In practice, systematic cleaning of the pyrometer optics is difficult.

This leads to a situation in which the pyrometer readings do not reflect effective variations of metal temperature.

It is possible to reduce the effect of the conditions detrimental to the quality of furnace temperature readings with the aid of a sensory element (heat receptor) placed in immediate proximity to the body whose temperature is to be measured.

It is well known that the types of pyrometers in practical use in metallurgical production are not suited for work under such extreme conditions.

A proposal is made in the literature /3/ to measure temperature with the aid of heat-measuring devices placed inside the furnace.

Two variations of this type of heat-measuring device are currently known:

1) Double measurement by the system of the Moscow Steel Institute (MIS), whose active principle is based on measuring the heat flow by the temperature difference in cooling water prior to and after passing through the heat receptor.

2) The VNIIMT (All-Union Scientific Research Institute of Metallurgical Thermotechnics) system which uses the temperature differences on a heat resistor to measure heat flow.

Both these heat-measuring devices have weaknesses. The MIS device is complicated to build, has great inertia, and provides readings which are highly dependent on the flow of water through the heat receptor.

The device built on the VNIIMT system is simpler and more convenient, but its measurement accuracy is low as a result of varying coefficients of heat conductivity as the temperature of the heat receptor material changes, and also of varying degrees of blackness of the surface of the heat receptor. Besides, the sensitivity of the instrument is low, since temperature difference is measured only by differential thermocouple.

The radiation heat meter (The text reads "heat meter MP", but an addendum indicates that this is a printer's error. --translator) developed by the authors has none of these weaknesses and dependably measure emission heat flows.

Basis for method of measurement

The active principle of the radiation thermometer lies in the measurement of a temperature drop induced in a heat resistor by a heat flow which the heat receptor got from the emitter.

The heat receptor is seen to be a form of ideal black body. Such a form may be represented by a small opening in the wall of an opaque, hollow body (a sphere, for example) with equal temperature.

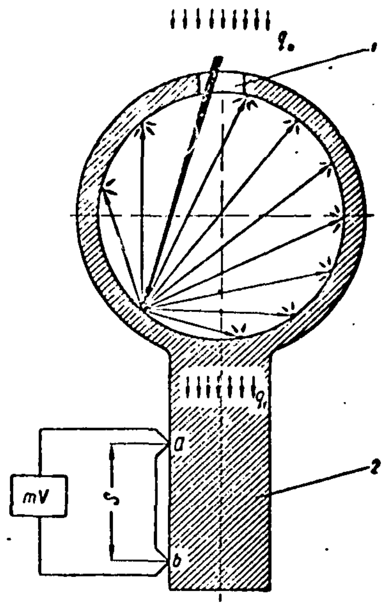

Figure 1. Diagram of the measuring element of the radiation thermometer: 1 - heat receptor: 2 - cooled shank.

Any heat ray passing through the opening into the cavity of the sphere (Figure 1) will, by multiple reflection, be completely absorbed and will not escape even though the inter[illegible]urface of the cavity walls be highly reflective.

Let us now suppose that the outer surface of the sphere is heat insulated from the surrounding medium and that heat entering through opening $\underline{1}$ is eliminated from the sphere by shank $\underline{2}$. the tip of which is cooled. At distance $\underline{S}$ from each other on the shank are located the active junctions of two differentially connected thermocouples.

Between the measurable heat flow $\underline{q_0}$ and the quantity of heat $\underline{Q}$ caught by the heat receptor under conditions of hemispherical exposure, there exists the following relation:

$$Q = q_0 F_0 \ \underline{\text{kcal/hour}} \tag{1}$$

where F_0 -- the area of the inlet opening of the heat receptor.

The heat flow q_1 passing down the shank depends on the cross-sectional area $\underline{f}$ of the shank

$$q_1 = \frac{Q}{f} = q_0 \frac{F_0}{f} \ \underline{\text{kcal/sq m/hour}} \tag{2}$$

We shall call the value $\frac{F_0}{f}$ the coefficient of heat flow increase and designate it by the letter $\underline{k}$. If $\underline{k} = 1$, this means that the heat flow $\underline{q_1}$ along the shank is equal to $\underline{q_0}$ being measured. When $\underline{k} \neq 1$, the value $\underline{q_1}$ differs from $\underline{q_0}$ by $\underline{k}$ number of times.

$$q_1 = kq_0 \tag{3}$$

It is essential that the nature of the relation $q_1 = f(q_0)$ does not depend on the degree of blackness of the material from which the heat receptor is made, nor on the state of its internal surface (dustiness, acidity, etc.).

Moving along the shank, the heat flow $\underline{q_1}$ creates a temperature drop Δt between points $\underline{a}$ and $\underline{b}$ and the value of this drop depends on $\underline{q_1}$, the distance $\underline{S}$, and the coefficient of heat conductivity λ of the material of which the shank is made

$$\Delta t = \frac{q_1 S}{\lambda} \ {}^{\circ}C. \tag{4}$$

Substituting the value of $\underline{q_1}$ from equation (3) into this formula, we get

$$\Delta t = q_0 \frac{k}{\lambda} S \ {}^{\circ}C. \tag{5}$$

In as much as the values $\underline{k}$, λ, and $\underline{S}$ are constant for a given instrument structure, formula (5) may be presented in the form

$$\Delta t = k_1 q_0 \tag{6}$$

where

$$k_1 = \frac{kS}{\lambda} \tag{7}$$

Thus, a clear relationship exists between q_0 and Δt. With given values of $\underline{S}$, λ, and $\underline{k}$, a single value of Δt corresponds to each value of q_0.

In reality, any device built according to this diagram (figure 1) is going to measure not the absolute quantity of the heat flow entering the cavity of the sphere, but rather the difference Δq_0 between the heat flow q_0 entering into the cavity of the sphere from outside and the heat flow q_2 emitted from the cavity of the sphere to the surface through opening $\underline{2}$.

$$\Delta q_0 = q_0 - q_2 \ \underline{\text{kcal/sq meter/hour}} \tag{8}$$

In as much as $\varepsilon \approx 1$, the value q_2 depends only on the temperature t_{sph} of its internal surface.

When the tip of shank $\underline{2}$ is cooled with an unvarying intensity, to every value of heat flow q_0 there corresponds a fully determined wall temperature of the sphere. It is for this reason that the relation between Δt and q_0 is clear.

If, however, there are variations in the conditions of cooling the tip that might lead to some error in determining the value q_0, in as much as the wall temperature of the sphere t_{sph} would change somewhat with a resulting change in the value q_2.

However, as concrete calculations and experiments show, this error is so insignificant in calculating q_2 that it can practically be ignored.

Thus, for example, if the temperature of the surface emitting heat into the sphere is equal to 1700°C (we are assuming this surface to be ideally black) and the internal surface of the sphere has a temperature of 100°C, then the corresponding values of the heat flows will consititute

$$q_0 = 4.96\left[\frac{1700+273}{100}\right]^4 = 750{,}000 \text{ kcal/sq meter/hour},$$

$$q_2 = 4.96\left[\frac{100+273}{100}\right]^4 = 1000 \text{ kcal/sq meter/hour},$$

$$\Delta q_0 = q_0 - q_2 = 750{,}000 - 1000 = 749{,}000 \text{ kcal/sq meter/hour}.$$

As we see, the specific value q_2 is extremely small and amounts to

$$\frac{q_2}{\Delta q}100\% = \frac{1000}{749{,}000}100\% = 0.13\%. \qquad (9)$$

If the conditions for cooling the tip were to change to the extent that the wall temperature of the sphere were to become 150° (by varying the temperature of the water cooling the tip, for example), under those conditions

$$q_{2(150^\circ)} = 4.96\left[\frac{150+273}{100}\right]^4 = 1600 \text{ kcal/sq meter/hour} \qquad (10)$$

$$\Delta q_0' = q_0 - q_{2(150^\circ)} = 750{,}000 - 1600 = 748{,}400 \text{ kcal/m}^2\text{/hour}.$$

The error in measurement δ brought about by changing the temperature of the inner surface of the ball by 50°C would constitute, under these conditions,

$$\delta = \frac{\Delta q_0 - \Delta q_0'}{\Delta q_0}\cdot 100\% \quad \frac{749{,}000 - 748{,}400}{749{,}000}\cdot 100\% = 0.08$$

It is quite understandable that such an insignificant amount of error is practically undetectable. This method may be used not only for measuring the heat flows q_0, but for measuring the temperature of heated surfaces as well. This latter effect stems directly from the Stefan-Boltzmann law

$$q_{\ell} = C\left[\frac{T_{sur}}{100}\right]^4 \quad \underline{\text{kcal/sq meter/hour}}.$$

Having used this method to determine the value of the heat flow q_{ℓ}, and knowing the value $\underline{C}$, it is possible to ascertain the temperature of the emissive surface

$$T_{sur} = 100\sqrt[4]{\frac{q_{\ell}}{C}}\ ^{\circ}K.$$

<u>Structure of the radiation thermometer</u>

The basic component of the instrument (figure 2) is a hollow copper cylinder with a diaphragm in the center section. The thickness of the cylinder walls and diaphragm does not exceed 0.2 mm. The portion of the cylinder above the diaphragm appears as a form of ideal black body and properly fills the function of a heat receptor.

Slits are made in the lower portion of the cylinder with the intervals between serving as heat resistors. The cylinder is fitted with a sleeve through which run the leads from the thermopile.

The thermopile is made up of copper-Constantan thermocouples by the galvanic system /4/. The number of thermocouples is determined by the sensitivity the instrument needs to have.

The thermopile is wound on the outer surface of the cylinder in such a way that the heat resistors fit between the junctions located on the surface of the heat receptor (hot junctions) and those junctions located on the water-cooled portion of the cylinder (cold junctions). Sheet mica is used to electrically insulate the surface of the cylinder from the thermopile. The thermopile is also covered over with a layer of mica. The leads from the thermopile are passed through the openings inside the cylinder and taken out through the sleeve.

The heat receptor with the thermopiles are fitted into a jacket which protects them from water. Shiny, nickel-plated foil shielding

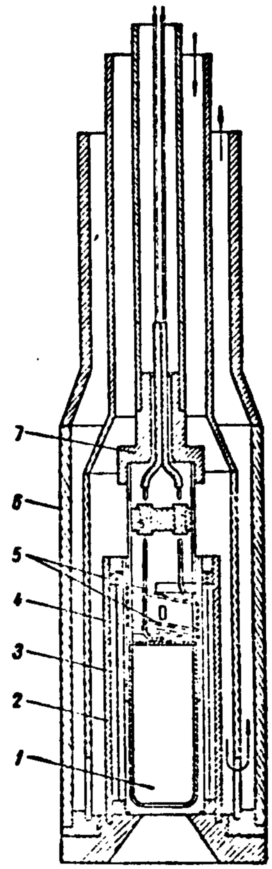

Figure 2. Structure of the radiation thermometer: 1 - heat receptor; 2 - protective jacket; 3 - shielding; 4 - thermopile; 5 - heat resistors; 6 - water-cooled body; 7 - sleeve.

is placed between the heat receptor and the jacket. This shielding contributes to minimum heat loss through the side walls of the heat receptor.

Thanks to its water-cooled body, the radiation thermometer may be set up in immediate proximity to the emitter.

The heat receptor with the thermopile, the protective jacket, and the shielding are brought together in a single unit which is fastened in the face of the water-cooled body by a special collar of red copper.

Two connecting pipes are fitted to the opposite end of the body for supply and discharge of water, and also with an adapter block for attaching the leads from the thermopile to a secondary instrument (potentiometer).

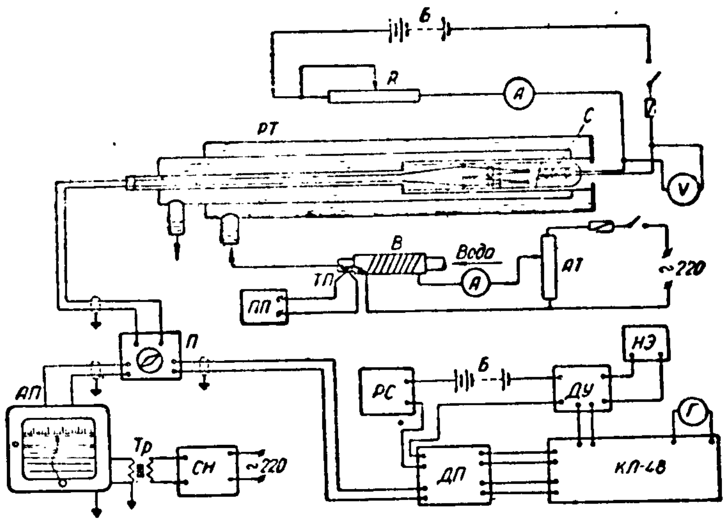

Figure 3. Diagram of device for testing the radiation thermometer:
RT - radiation thermometer; R - rheostat for regulating the heater current; B - storage battery; S - spiral heater coil; W - water heater; TC - thermocouple; PP - portable potentiometer; AT - autotransformer; P - switch; AP - automatic potentiometer; TR - separating transformer; VR - voltage regulator; KL-48 - laboratory potentiometer; G - galvanometer; RE - rated element; RR - regulated resistance; DP - double switch; SD - supplemental device operating as a unit with the KL-48.

Figure 3 presents the diagram of a device for testing the performance of the radiation thermometer.

The heating coil S, supplied with current from storage battery B, is placed in heat receptor RT. The amount of current in the coil is controlled by rheostat R. Heat loss into the surrounding space is reduced by careful insulation of the leads to the heater coil and the inlet opening of the thermometer.

The radiation thermometer is cooled by a circulation of water passing through the water heater W. The autotransformer AT can be used to control current flow into the element of the water heater and by this, the temperature of the water used to cool the heat receptor. The water temperature is measured by the thermocouple TC with the potentiometer PP. The e.m.f. of the thermometer is measured by a laboratory potentiometer, type KL-48. When registering time responses, the thermometer readings are inscribed on a graph tape by the automatic potentiometer AP.

Radiation thermometer e.m.f. in relation to measured heat flow[1].

Current I is regulated into the heater coil S by rheostat R. After a lapse of several minutes required for termination of the transitional process in the heater coil and establishing a new equilibrium state between the heater and the heat receptor of the radiation thermometer, the e.m.f. level of the thermometer is measured.

The amount of heat given off by the heater in a unit of time is

$$Q = 0.24UI \text{ calories/hour} \tag{11}$$

Since the heat loss into the surrounding space is insignificant, it may be accepted that the heat receptor takes up the entire quantity of heat Q.

Let us suppose that the heat receptor of the radiation thermometer is taking in radiation from an external emitter which might be a body heated to a determined temperature. In such a case, the amount of heat taken up by the heat receptor is determined by the ratio

$$Q = q_0 F_0 \text{ calories per hour} \tag{12}$$

where q_0 -- the heat flow created by the external emitter under hemispherical exposure in calories per square meter per hour;

F_θ -- the cross-sectional area of the inlet opening of the heat receptor in square meters.

According to equation (2).

$$q_\theta = \frac{Q}{F_\theta} \ \underline{\text{cal/sq. meter/hour}} \tag{13}$$

and substituting into this equation the expression for $\underline{Q}$ from equation (11), we get

$$q_\theta = \frac{0.24UI}{F_\theta} \ \underline{\text{cal/sq meter/hour}}. \tag{14}$$

We express the heat flow $\underline{q_\theta}$ from the emitter to the heat receptor with the aid of the Stefan-Boltzmann law

$$q_\theta = C\left[\left(\frac{T_e}{100}\right)^4 - \left(\frac{T_{HR}}{100}\right)^4\right] \ \underline{\text{cal/sq meter/hour}} \tag{15}$$

where $\underline{C}$ -- the corrected coefficient of radiation of the emitter in the emitter-heat receptor system;

T_e -- temperature of the emitter, $^\circ$K ;

T_{HR} -- temperature of the heat receptor, $^\circ$K .

The thermometer is so constructed that when measuring temperatures in the range from 600 to 1500° C, the temperature of the heat receptor varies within the limits of 50 to 150° C. In connection with this, the value $(\frac{T_{HR}}{100})^4$ is considerably lower than the value $(\frac{T_e}{100})^4$ and it may be neglected for an error on the order of 0.02%. Then formula (15) may be presented in this form:

$$q_\theta = C\left[\frac{T_e}{100}\right]^4 \underline{\text{cal/sq meter/hour}} \tag{16}$$

Solving equation (16) for $\underline{T_e}$ and substituting the value of $\underline{q_\theta}$ from equation (14), we get an expression for the calculation of $\underline{T_e}$

$$T_e = 100\sqrt[4]{\frac{0.24UI}{F_\theta}\,C} \ ^\circ\text{K}. \tag{17}$$

The ratios of the radiation thermometer's e.m.f. to the heat flow emitted by the object being measured, and also to its temperature, are presented in figure 4.

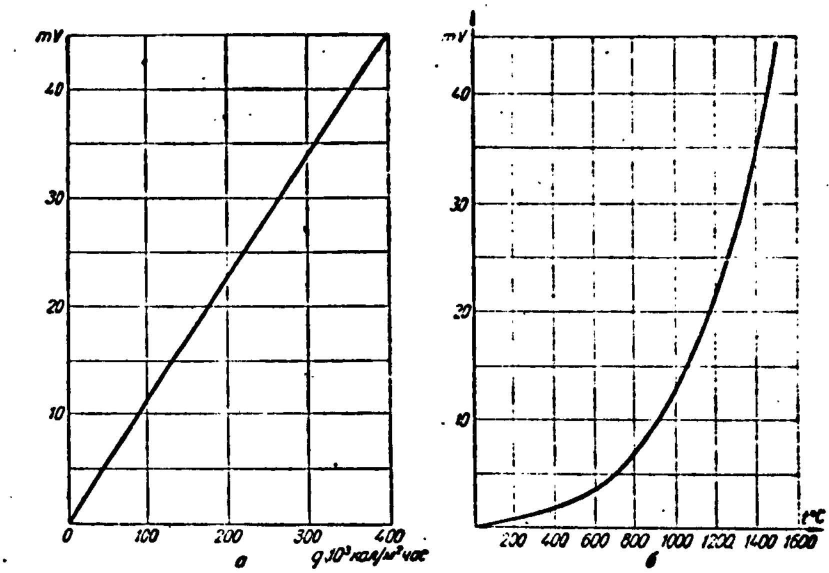

Figure 4. Response of the radiation thermometer:
a - by heat flow; b - by temperature.

Determining the inertial properties of the radiation thermometer

The inertial properties of temperature sensors are characterized by a constant lag ε, i.e. an interval of time expressed in seconds during which interval the difference between the sensor reading, expressed in degrees, and the temperature of the object being measured declines to 0.368 of its initial value, $0.368 = 1/e$ ($e = 2.718$ - base of the natural logarithms).

This determination of ε is applicable only for regular stages of the heating or cooling process.

The constant lag ε is determined in this manner.

The rheostat R is set to supply heater coil S with current I (figure 3), the value of which is held constant. After establishing a stable thermometer reading, the coil is quickly withdrawn from the heat receptor. The variation in thermometer e.m.f. resulting from the cooling is registered with the aid of the automatic potentiometer and

and recorded on graph tape. The test is repeated several times.

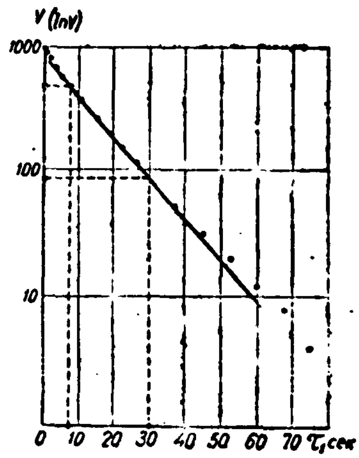

Figure 5. Determination of the constant lag ε.

Based on data from the tape, a graph is constructed (figure 5) with natural logarithm values of the difference between the steady and flowing rates of the thermometer reading set out on the axis of the ordinate and the corresponding units of time indicated on the abscissa.

From the graph presented here it can be seen that, starting with a given moment of time, the experimentally obtained points are distri - buted approximately on a straight line. The regular stage of the process approaches this.

The cotangent of the slope angle of this straight line to the axis of the abscissa represents the constant of sensor lag.

For the practical determination of ε, we chose two moments of time far enough apart, while still within the limits of the regular stage of the process.

The constant lag was calculated by the formula

$$\varepsilon = \frac{\tau - \tau}{\ln V_1 - \ln V_2} \text{ sec.} \qquad (18)$$

Correspondingly, for the cooling process the following values were obtained:

τ_1 = 7.5 sec; $\qquad V_1$ = 6.2025;

τ_2 = 30 sec; $\qquad V_2$ = 4.4773;

$$\varepsilon = \frac{30 - 7.5}{6.2025 - 4.4773} = 13 \text{ sec.}$$

The constant lag was only determined for regular stages of the cooling process since the effects of the transitional processes in the heating coil were thus eliminated.

Effect of cooling conditions on thermometer readings

After placing the heater in the heat receptor and establishing current <u>I</u>, a time lapse is allowed for fixing the thermometer reading. Water of temperature t_1 is supplied in the cooling system. The water flow is held constant.

After a stable reading has been established, we begin to feed water of temperature t_2, which may be either higher or lower than t_1, into the cooling system. The initial moment of supplying water of temperature t_2 is noted on the graph tape.

When a new equilibrium state has been reached, water of temperature t_3 is fed into the cooling system, and so on.

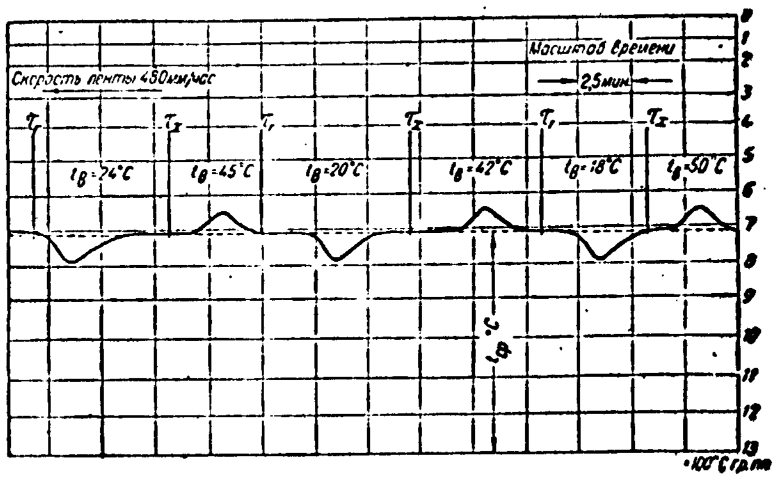

Figure 6. The effect of the intensity of cooling on the readings of a radiation thermometer: t_w - water temperature; t_{av} - average steady value of the thermometer reading; $\tau_x \tau_p$ - moment when water temperature was varied.

From an analysis of the results of the experiment (figure 6), the conclusion may be drawn that , in a stationary situation, the readings of the radiation thermometer do not depend on the intensity with which the heat receptor is cooled.

Determining distance from the object being measured

If the radiation thermometer is to operate correctly, it is necessary that the viewing angle of the instrument take in the entire emitting surface of the object whose temperature is to be measured.

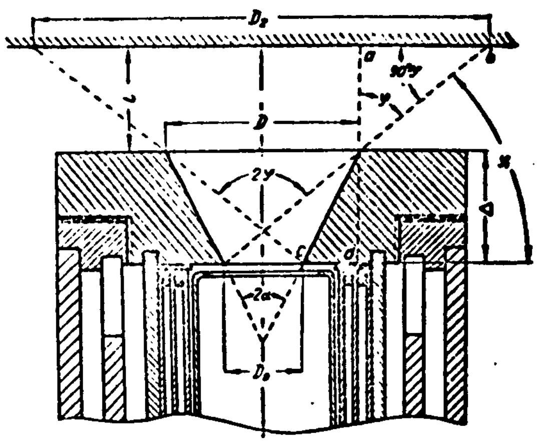

Figure 7. For determining the distance from the radiation thermometer to the emitter:
D_2 - diameter of the emitting surface; L - distance from the thermometer to the emitting surface; D - outer diameter of the thermometer inlet opening; D_0 - inner diameter of the thermometer inlet opening; 2φ - sighting angle; 2α - bore angle of the collar; Δ - thickness of the collar.

In order to correctly select the distance L from the thermometer to the object measured, some relationship must be established between L and some geometric value characterizing the construction of the thermometer.

Making a calculation according to figure 7, we obtain a simple ratio relating the basic dimensions of the inlet opening of the thermometer to the distance L to the body whose temperature is being measured, and the minimum diameter D_2 for measuring the temperature of the emitting surface

$$L = \Delta \frac{D_2 - D}{D_0 - D}.$$

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Footnotes

1. The method was suggested by the Department of Metallurgical Furnaces of the Dniepropetrovsk Institute of Metallurgy (DNIEPROPETROVSKII METALLURGIChESKII INSTITUT).

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