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Experimental Analysis of Radiative Heat Interchange on Furnace Exit Plane of a Steam Boiler

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Measured radiative heat fluxes on the furnace exit plane of a heavy duty power boiler of steam output 1650 T/h are discussed. A high-ash pulverized bituminous coal was used. Such measurements are necessary to improve heat transfer calculation in boiler furnaces. A radiometric probe for measuring radiative heat fluxes inside a steam boiler furnace was manufactured. An extra small heat radiation sensor was placed in the water cooled head of the probe. The sensor had no direct contact with furnace gases and measured only the radiant energy. There was no exposure to convective heat transfer. With the radiometric probe, one can obtain a spherical indicatrix of radiation intensity as well as hemispherical radiative heat flux incident on any surface passing through a measuring point inside the furnace. Thus, the quantity of radiation energy, passing through the furnace exit plane, to the convective heating surfaces and the quantity of radiation energy going in the opposite direction were measured. A formula for relative radiative heat flux on the furnace exit plane has been proposed.

Key Words : Steam Boiler Furnace, Radiometric Probe, Spherical Indicatrix of Radiation Intensity

1. Introduction

The progress in the development of modern heavy duty power steam boilers depends on the thermal calculation of boiler units, especially the calculation of furnace heat reception. The furnace heat reception determines unequivocally the combustion products temperature at the furnace exit plane (the furnace output window) θ_F. This temperature is used when designing the convection heating surfaces of a steam boiler.

A great deal of research in the field of thermal calculation of steam boiler units was conducted in Russia since the Second World War, and generalized by A. M. Gurvich in a monograph (Gurvich, 1950). At the Polzunov Central Boiler and Turbine Institute (NPO CKTI, Leningrad, Russia), a method of thermal calculation of boiler aggregates was developed (Kuznetsov et al., 1973). Using this method it is possible to calculate the temperature of combustion products leaving the furnace of a boiler. This method has been widely used in Russia, East Europe and China.

The surface of a furnace exit plane is a component of the total surface forming the furnace chamber. Water-steam tubes are located at the furnace wall heating surfaces, and heat reception occurs by radiation and convection. However, the furnace exit plane does not contain heating surfaces. Some of the heat released in the furnace enters the furnace output window by radiation and passes completely to heating surfaces located out of the furnace. It is clear that a quantity of radiant energy leaving the furnace exit plane ΔQ influences the formation of the combustion products temperature θ_F.

The normative method of thermal analysis of steam boiler furnaces, stated in (Kuznetsov et al., 1973), is based on experimental research in which

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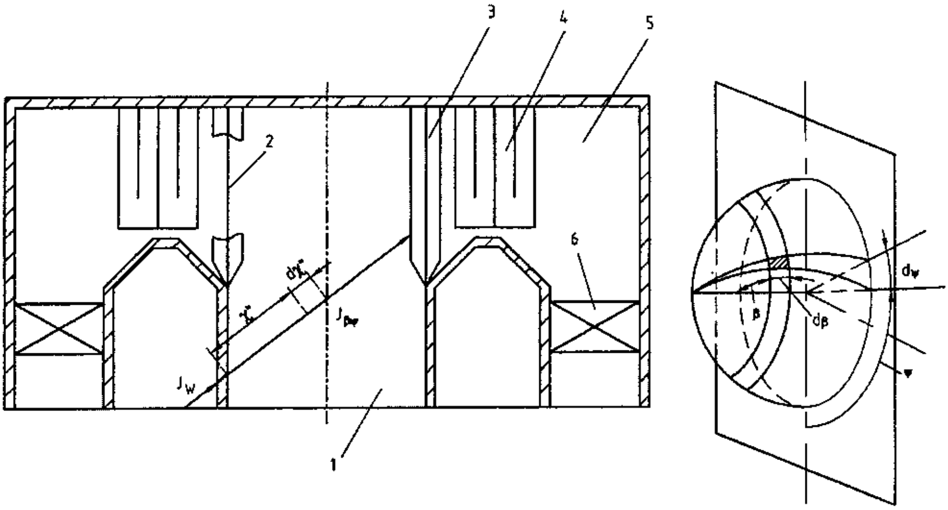


1. Furnace top; 2. Furnace exit plane; 3. Furnace outlet screen;
4. Platen superheater; 5. Horizontal gas duct; 6. Convection superheater.

Fig. 1 Schematic for analyzing radiative heat transfer on the furnace exit plane of a steam boiler

the temperatures of combustion products θ_F for many boilers were measured. However, the direct measurement of radiant energy ΔQ was not carried out. Therefore, the accuracy of calculating θ_F was not high. In additional research on the heat transfer in steam boilers (Shatil and Danilovtsev, 1974; Shagalova and Shnitser, 1976; Pomerantsev, 1986; Shatil, 1986), the results of experimental definition ΔQ had not been considered.

In the design of modern steam generators it is necessary to determine the heat quantity transferred by radiation from the furnace through its exit plane up to the platen superheater, arranged outside the furnace.

In Fig. 1 the outline of the furnace exit plane (the furnace output window) and the arrangement of heating surfaces in the top of the steam boiler under investigation are shown. The task was to determine the resultant quantity of radiation energy transferred from the furnace to the furnace outlet screen, platen superheater, ceiling and lateral screens arranged behind the furnace exit plane. This resultant quantity of radiation energy represents a difference $\Delta Q = Q^{+} - Q^{-}$, where Q^{+} is the quantity of radiant energy incident on the furnace exit plane in the direction away from the furnace and Q^{-} is a quantity of a radiation energy going in the opposite direction (i. e. from the screens to the furnace). The value of Q^{+} is due to generation and absorption of radiation energy within the firing space. The character of heat release in the furnace, the distribution of combustion products, their concentration, density, temperature, emission properties as well as the temperature and the properties of furnace walls are not the complete list of factors affecting the numerical value of Q^{+}. A theoretical solution of the radiant heat fluxes passing through a furnace exit plane is complicated.

In this paper the measurements of radiative heat fluxes on the furnace exit plane are considered. Also a formula for estimating relative heat flux on the furnace exit plane is proposed.

2. Analysis of Radiative Heat Transfer on the Furnace Exit Plane

In the present analysis it is assumed that the furnace medium is a gray radiating and absorbing medium. Using the equation of radiation energy transfer in a radiating and absorbing medium (Antonovsky, 1998) we can write an expression for the heat radiation intensity reaching an element of the furnace exit plane in a direction, defined by angles β and ψ, (Fig. 1) as:

$$J_{\beta\psi}=J_W\exp(-\chi)+\int_0^{\chi}\exp[-(\chi-\chi^*)]J_b(\chi^*)d\chi^* \tag{1}$$

where χ is the optical density, and

$$J_w=\sigma\varepsilon_w T_w^4/\pi+J_{Ref} \tag{2}$$

represents the effective radiation intensity of the furnace wall in the direction considered. The quantities ε_W and T_w are the emissivity and temperature [K] of a wall element, which is assumed to be diffuse. J_{Ref} is the radiation intensity reflected from the wall. In Eq. (1), $\chi=kL$ is the optical density of the medium, k is the absorption coefficient of the medium; L is a beam length and χ^* is the current optical density value; $J_b=(1/\pi)\sigma T^4$ is radiation intensity of a blackbody, whose temperature is equal to the local temperature T [K] of the medium.

To determine the incident hemispherical radiant heat flux going from the furnace to the element of the furnace exit plane under consideration, it is necessary to have at one's disposal the radiation intensity $J_{\beta\psi}$ in every direction within the limits of a hemisphere ($\beta=0\rightarrow\pi/2$; $\psi=2\pi$):

$$q^+=\int_{2\pi}J_{\beta\psi}d\Omega=\int_{\psi=0}^{2\pi}\int_{\beta=0}^{\pi/2}J_{\beta\psi}\sin\psi\cos\beta d\beta d\psi \tag{3}$$

Here Ω is a solid angle with its vertex situated on the furnace exit plane element considered.

The total radiation energy reaching the furnace exit plane can be determined by integrating q^+ within the total surface of the furnace exit plane S:

$$Q^+=\int_S q^+ds \tag{4}$$

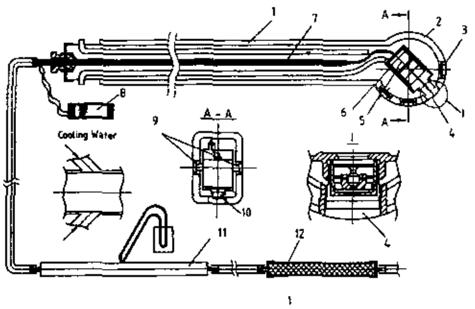
Q^- is determined by radiation and absorption of the combustion products in the region of furnace outlet screen and platen superheater and radiation from their surfaces. Q^- can be calculated by equations analogons to Eq. (1), (2), (3) and (4).

3. Radiometric Probe

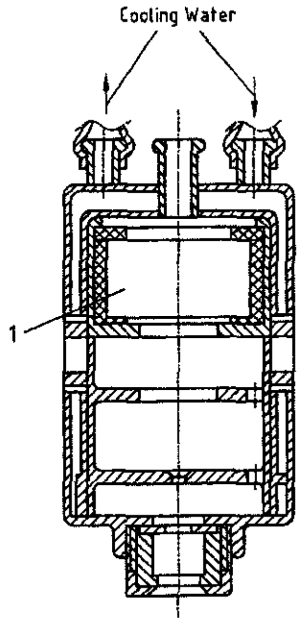
It is necessary to take into account the quantity of radiant energy $\Delta Q=Q^+-Q^-$ to calculate the furnace heat absorption and the combustion products mean temperature in the exit furnace plane. It is also necessary to take into account the value of ΔQ when calculating the heat absorbed, for example, by a platen superheater. Moreover, the quantity of radiant energy mentioned is necessary to estimate for an experimental study of heat transfer in a steam boiler furnace. In this case, as a rule, one tries to determine the mean combustion products temperature θ_F, because this value characterizes the furnace heat absorption. However directly measuring θ_F (1200℃ and even higher) with a suction pyrometer steam boilers is difficult because of large furnace size and temperature non-uniformity of combustion products at the furnace exit plane. It is expedient to measure θ_F by means of an indirect method. Measuring, the combustion products temperature in the duct cross-section behind the platen superheater and in front of the convective heating surfaces is an example. At this position the temperature level is much lower than θ_F and direct temperature measurements with many fixed thermocouples is not difficult. From the measured heat absorption of the heating surfaces (situated between furnace exit plane and the duct cross section), and the mean combustion products temperature in that cross section, one can determine θ_F. ΔQ value is still needed.

We have designed, made and applied a radiometric probe for radiant heat transfer meas mement in the volume and on the boundaries of the firing space in an operating heavy duty boiler furnace. The devices distinctive feature is the incorporation of a very small radiant energy detector in the cooled head of the probe. The optical axis of the detector can be turned inside the probe head. Thus, the flame radiation intensity in the firing furnace volume can be determined. The probe can measure incident radiation near the furnace walls as well as radiation from the opposite direction. The radiometric probe is used to measure radiant energy near the furnace exit plane of some steam boilers. These measurements are described in this paper.

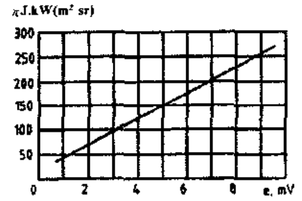
The schematic of the radiometric probe is shown in Fig. 2. It consists of a water-cooled



(a) Schematic of the radiometric probe



(b) Capsule



(c) Calibration characteristic

Fig. 2 Radiometric probe

body (Part 1), and head (Part 2). The inner cavity of the head is cylindrical with its axis perpendicular to the centerline of the Part 1. Holes Part 3 (3 and 4) are placed on the cylindrical surface of the head. The angle β between the hole axis and the body centerline can vary from 0° to 135°. The small infra-red detector (Part 5) is placed inside a cylindrical copper capsule (Part 6). The capsule and a viewing hood with diaphragms are made with double walls. In the space between the walls, cooling water from an independent water supply circulates. The detector leads are installed inside a flexible tube (Part 7), which also serves as a passage for a small inert gas flow. The recording instrument (Part 8) records the detector signal. Before inserting the probe into the firing space, the capsule (Part 6) should be rotated on the axis (throngh Part 9) and properly fixed concerning the head with the help of a block of diaphragms (Part 10). Thus the centerline of the detector will coincide with the axis of one of the holes. The detector "sees" a volume in the direction of the detector centerline. The solid angle of vision, determined by the edges of the diaphragms, is about 0.01 steradian and can be varied by changing the diaphragms. The holes not in use are covered by removable plugs. A small amount of inert gas or dry clean air is admitted to the inner cavity of the capsule through a flexible tube (Part 7). Therefore, the combustion products cannot hit the inner cavity of the viewing hood, and, thus, do not affect the accuracy of radiation measurements. The amount of inert gas is measured on site (Part 11). Before entering the probe, the inert gas is cleaned by the filter (Part 12). The measurements are performed at a constant boiler load.

It is necessary to emphasize that in the radiometric probe the detector is not in direct contact with combustion products. It is affected only by heat radiation. The effect of convection on the device signal is eliminated. This is the principal difference between our radiometric probe and the well-known heat flux meter whose sensor is in direct contact with combustion products.

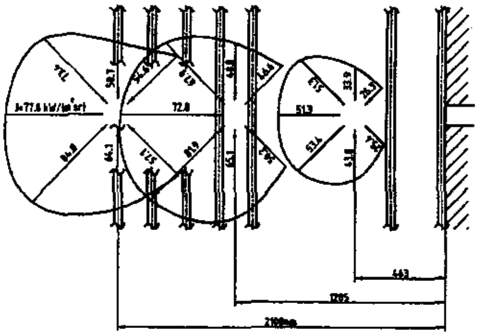
After preparation, the probe is inserted into an inspection hole of the furnace to a predetermined position so that the head of the device is at the desired point in the firing space. At each fixed angle β the measurements are taken at various values of angle ψ around its centerline ($\psi=0°$ to 360°) in increments of $\Delta\psi$. Traversing for angle β and placing of the capsule inside the probe head are done manually before each immersion of the probe inside the furnace space. If a full set of measurements ($\beta=0°$ to $180°$; $\phi=0°$ to $360°$) are taken at a giwen point, one will receive a spherical indicatrix of radiation intensity. Actually, the design features of the probe only allow a change of the angle β between 0° and 135°. Nevertheless, a set of measurements of radiation intensity $J_{\beta\phi}$ at a point inside the furnace space has permitted the measurements of the incident hemispherical radiation flux on an area element, passing through a measuring point. For example, the incident radiation flux on the area element, passing through the measuring point and perpendicular to the centerline of the probe, can be determined according to Eq. (3) which can be solved numerically from the measured values of $J_{\beta\phi}$.

4. Steam Boiler

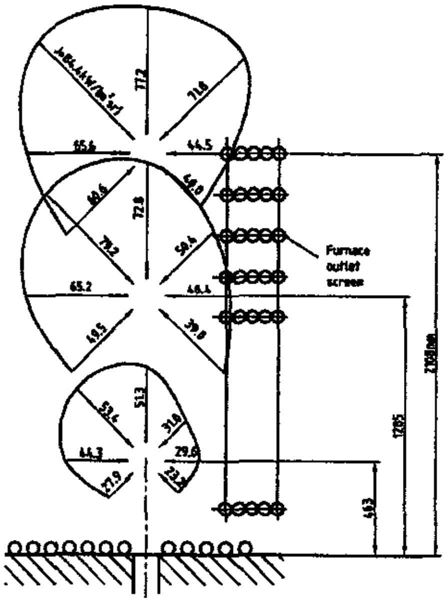
The experiment was performed on a power plant steam boiler having steam output of 1650 T/h. A high-ash pulverized bituminous coal was used for fuel. The ash content was as high as 40 %. The boiler had a T-shape layout. It means an almost-symmetric boiler with its furnace at the center. The prismatic furnace had a cross-section of 10×22 m. The furnace height was 49.5 m. There were 24 cyclone-type burners arranged face to face in two circles. The furnace was screened by all-welded panels. The fuel was prepared by direct fuel-air injection with 8 hammer grinding mills having fuel output of 40 T/h.

5. Observed Data

The radiant energy data in the firing space, measured near the furnace exit plane, are shown in Fig. 3. The radiation intensity measurements $J_{\beta\phi}$ were made at several points on the center line of an inspection hole at different distances of the probe head from the furnace wall. The maximum insertion distance was 2108 mm. Because of the difficulties of $J_{\beta\phi}$-plotting on a flat drawing, the three-dimensional values of $J_{\beta\phi}$ in the vertical and horizontal planes are plotted in Fig. 3. The distribution of incident hemispherical heat radiation fluxes q^+ and q^- on the furnace exit plane can be seen in Fig. 4. The distribution of the difference $\Delta q=q^+-q^-$, on the transmission of radiation energy from the furnace to the furnace outlet screen, is also shown in Fig. 4.



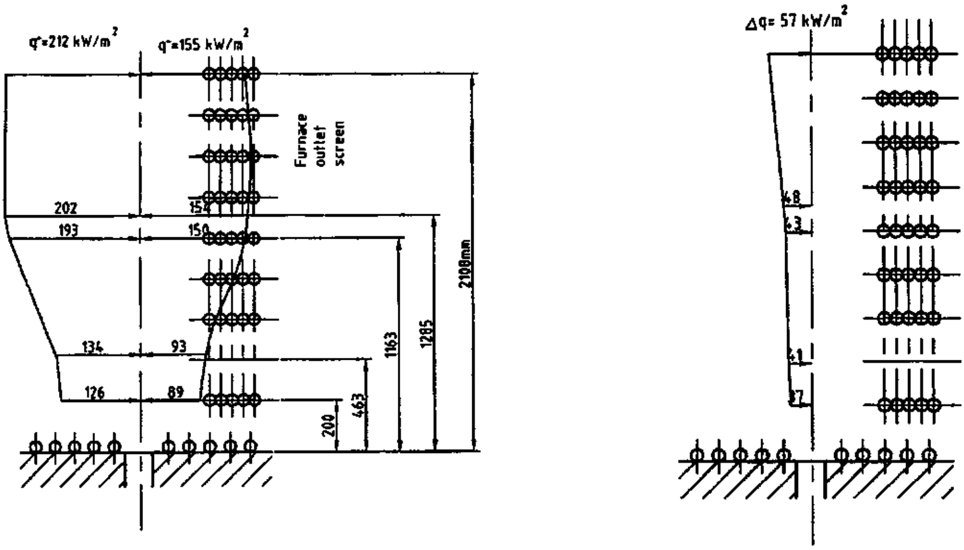
(a) Vertical plane



(b) Horizontal plane

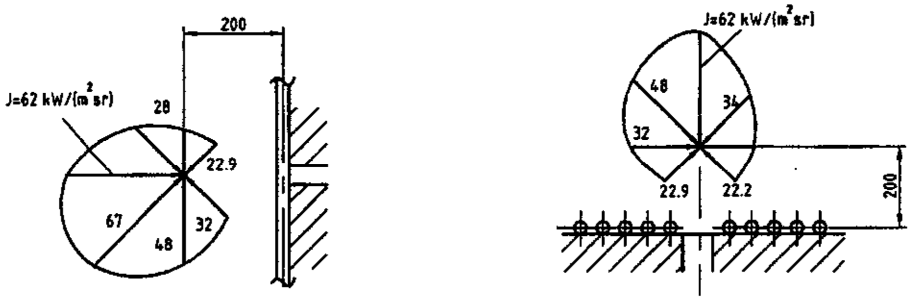
Fig. 3 Spherical Indicatrixes of heat radiation intensity on the furnace exit plane

The radiation intensity from the bottom layers of the furnace, where temperature can exceed 1500℃, is suppressed by the upper layers with a lower temperature of about 1200℃. In the firing space the distinctly expressed not diffuse radiation takes place. As the probe is inserted deeper into the furnace, radiation intensity $J_{\beta\phi}$ increases in all directions. As the distance between the probe head and the wall increases, the values of q^+, q^-



(a) Distribution of incident hemispherical heat radiation fluxes q^+ and q^- in the horizontal plane

(b) Distribution of the difference $\Delta q=q^+-q^-$ in the horizontal plane



(c) A fragment of the spherical indicatrix of heat radiation intensity, cross-section in a vertical plane

(d) A fragment of the spherical indicatrix of heat radiation intensity, cross-section in a horizontal plane

Fig. 4 Results of measurement of radiation energy in the region of the furnace exit plane

and $\Delta q=q^+-q^-$ increase. At the furnace exit plane, the mean value of measured Δq was 54 kW/m².

The figure of merit $\varphi=(q^+-q^-)/q^+$ is used in furnace thermal calculation (Kuznetsov, 1973). In our experiments we obtained $\varphi=0.27$. The figure of merit φ is similar to the thermal efficiency of the wall screen heating surfaces, i. e. it indicates radiative heat, perceived by the furnace exit plane as a fraction of the incident heat radiant flux q^+. It is necessary to keep in mind, that in this case q^- was not a consequence of the radiant flux q^+, but was stipulated predominantly by radiation of combustion products in the horizontal duct in the direction towards the furnace exit plane.

6. Estimation of the Figure of Merit φ

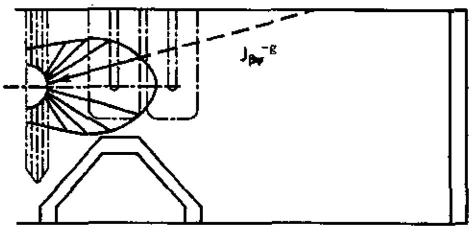
An engineering method of calculating φ from radiant energy measurements is proposed in this section.

Let us represent the radiant flux q^-, going from the furnace outlet screen to the furnace exit plane as the sum:

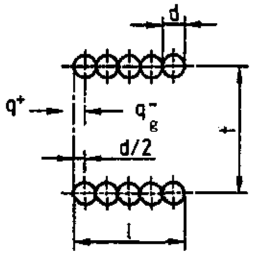
$$q^-=rq_g^-+(1-r)q_w^-, \tag{5}$$

where $r=(S-s)/S=S_1/S$;

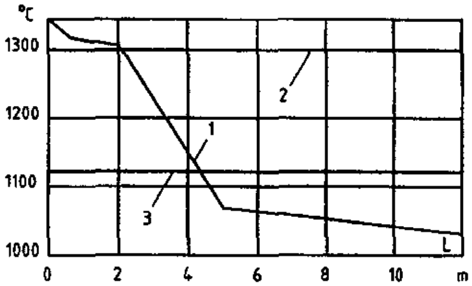
S is the surface of the furnace exit plane; s is the



(a) Formation of the radiation intensity and hemispherical radiation flux behind the furnace exit plane



(b) A fragment of the furnace outlet screen pipes



(c) Schematic for calculating $J_{\beta\varphi}^{-g}$ — 1) Temperature distribution of the combustion products within the beam length; 2) Effective radiation temperature; 3) Average temperature of the combustion products.

Fig. 5 Schematic for the conclusion of the correction coefficients Π_θ and Π_k

area of pipes in the duct cross section directly behind the furnace exit plane; q_g^- is the mean incident hemispherical radiant flux on the surface S_1; and q_w^- is the mean incident hemispherical radiant flux on the surface s.

The adopted notation is illustrated in Fig. 5. The design formula for the figure of merit φ can be given as:

$$\varphi = (1 - r q_g^-/q^+) - (1-r)(\varepsilon_w \sigma T_w^4/q^+ + 1 - \varepsilon_w) \tag{6}$$

where T_w and ε_w are the temperature and emissivity of the first row of furnace outlet screen pipes (or platen superheater pipes), sespectively.

Let us estimate the contribution to the heat flux q^- by radiation from the first row of pipes q_w^-. From Eq. (5) we have:

$$q_g^- = q^-/r - (1-r)[\varepsilon_w \sigma T_w^4 + (1-\varepsilon_w) q^+]/r \tag{7}$$

According to Eq. (7), a number of calculations q_g^- for all sets of measurements were made. ε_w was assumed to be 0.8. Temperature T_w [K] was determined according to Kuznetsov N. et al. (1973). Analysis shows that the $(1-r)\, q_w^-$ term contributes less than 4 % to the radiant flux q^-. Thus, the predominant effect on the characteristic φ in Eq. (5) is rendered by the first term. Note that the numerous measurements of radiation show that q^-/q^+ at the furnace exit plane is stable and lies between 0.73 to 0.77. This result simplifies the generalization of the measured experimental material.

Major factors influencing the relative radiant flux q_g^-/q^+ are the temperature of gases escaping the furnace, θ_F, and the optical density of gases within the horizontal gas duct, especially near the furnace exit plane. Keeping in mind the rather narrow range of change q_g^-/q^+ in actual boilers, let us take into account only main factors that influence the value of q_g^-/q^+. With this purpose we can express q_g^-/q^+ as

$$q_g^-/q^+ = \Pi_\theta \Pi_k (q_g^-/q^+)^* \tag{8}$$

where Π_θ is the correction coefficient which takes into account the effect of gas temperature θ_F. Π_k is the correction coefficient which takes into account the effect of emitting and absorbing properties of gases and the geometry of heating surfaces. $(q_g^-/q^+)^*$ is value of (q_g^-/q^+) for $\Pi_\theta = 1$ and $\Pi_k = 1$.

The dependence of the relationship Π_θ on θ_F can be determined by noting that, at the furnace exit plane, q^+ is proportional to $(\theta_F + 273)^4$. The furnace output window "sees" in directions perpendicular to the plane under consideration those regions in the furnace space, which are arranged at the same level, i. e. have the same gas temperature. Taking this into consideration, we can find from Eq. (8) :

$$\Pi_\theta=(1/\Pi_k)[q_g^-/(\theta_F+273)^4]/[q_g^-/(\theta_F+273)^4]^* \tag{9}$$

Values marked with an asterisk (*) are constant. Function $\Pi_\theta=f(\theta_F)$ is influenced only by $q_g^-/(\theta_F+273)^4$. The dependence of Π_θ on θ_F has been implemented as follows. In a set of experiments at different θ_F, the gas temperature distribution in the horizontal gas duct was determined. Thus, in each case, the temperature distribution within the beam length was determined. As for the radiant properties of combustion products with absorption coefficient k and surface temperatures T_w, they were determined according to (Kuznetsov, 1973). Thus, the values of q_g^- were calculated numerically via Eqs. (1), (2), and (3). In Fig. 5(a) intensity $J_{\beta\varphi}^{-g}$ is defined. Hemispherical radiation flux q_g^- is shown in Fig. 5(b). Information in a monograph (Kuznetsov, 1973) was used. It is noted that the greatest effect on the $J_{\beta\varphi}^{-g}$ and q_g^- was from gas layers situated close to the furnace exit plane. For a specified distribution of gas temperature along a beam length of L=12m and k=0.7 1/m in a horizontal boiler gas duct, the effective radiant temperature was 1300℃. At the same time the average value of gas temperature on the beam length mentioned earlier was equal to 1130℃.

Having computed $J_{\beta\varphi}^{-g}$ in different directions within the limits of a hemisphere and within the area S-s, the incident radiation energy on S-s could be determined by numerical integration of $J_{\beta\varphi}^{-g}$. Dividing the obtained value by S-s yields the average value of radiate heat flux, q_g^-, over the area S-s. Such experimental-computational results of $\Pi_\theta=f(\theta_F)$ are shown in Fig. 6(a). From this relation, the temperature of the gas θ_F^* at which $\Pi_\theta^*=1$ is taken as 1200℃.

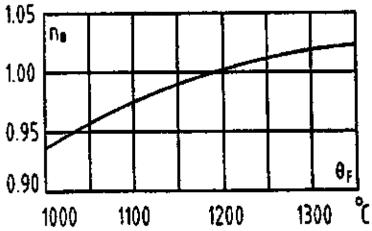
Now let us consider the correction coefficient Π_k. In addition to θ_F, the size of the furnace outlet screen and the emission absorption properties of the combustion products affect q_g^-/q. The heat radiation of gases from the horizontal gas duct at given temperature is determined by the gas emissivity, ε_{sc}:

$$\varepsilon_{sc}=1-\exp(-kL_{ef})$$

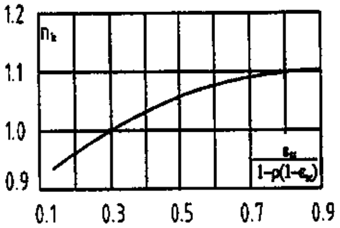
where L_{ef} is effective beam length, computed according to Kuznetsov (1973) as

$$L_{ef}=1.8/(1/H+1/t+1/l)$$

where H is the vertical size of the furnace outlet screen. Explanations concerning sizes l and t are displayed in Fig. 5(b).



(a) Π_θ versus θ_F



(b) Π_k versus $\varepsilon_{sc}/[1-\rho(1-\varepsilon_{sc})]$

Fig. 6 Value of correction coefficients Π_θ and Π_k

Only a fraction of the radiation, equal to $\rho(1-\varepsilon_{sc})$, reaches the furnace outlet plane. ρ is the angular factor of screens, calculated according to Kuznetsov(1973):

$$\rho=[(l/t)^2+1]^{0.5}-l/t$$

We have taken into account the parameter, $P=\varepsilon_{sc}/[1-\rho(1-\varepsilon_{sc})]$, which reflects the design features of screens and the radiant properties of the combustion products. A series of calculations to establish the relation $\Pi_k=f\{\varepsilon_{sc}/[1-\rho(1-\varepsilon_{sc})]\}$ was made for different combinations H, t, l at different absorption coefficients. The calculation procedure for establishing $\Pi_k=f(P)$ was the same as in the case of Π_θ. In Fig. 6(b), the dependence of Π_k on $\varepsilon_{sc}/[1-\rho(1-\varepsilon_{sc})]$ is shown. The parameter P^*, at which $\Pi_k^*=1$, is equal to 0.30.

Returning to the Eqs. (6), (7), and (8) we have

$$\varphi=[1-\Pi_\theta\Pi_k r(q_g^-/q^+)^*]-(1-r)(\varepsilon_w\sigma T_w^4+q^+-\varepsilon_w q^+)/q^+ \tag{10}$$

Neglecting the self-radiation, and back-radiation of the first row of screen pipes due to their smallsize and taking into consideration the actual ratio of d/t in boilers, we have obtained an expression for the figure of merit, φ, as

$$\varphi=1-\Pi_{\theta}\Pi_{k}r(q_{g}^{-}/q^{+})^{*} \tag{11}$$

Fig. 6 should be used for obtaining the correction coefficients Π_{θ} and Π_{k}. On the basis of direct measurements, $(q_g^-/q^+)^*$ is found to be equivalent to 0.72. With this value the Eq. (11) is applicable for boilers burning pulverized solid fuel.

7. Conclusion

From direct measurements of radiant energy in the furnace of a heavy duty steam boiler using a newly designed radiometric probe, the spatial distribution of radiation intensity at the furnace output window was obtained. At full-load, the mean value of the resultant radiant flux, Δq, escaping the furnace through the output window was 54 kW/m^2. The ratio q^-/q^+ varied between 0.73 and 0.77. A formula for calculating the figure merit φ has been proposed.

References

Antonovsky, V. I., 1998, "The Effect of the Flame Thermal Radiation in the Gas Turbine Combustor on the Turbine Vanes," *Turbine and Compressors*, Vol. 6, 7, pp. 23~25.

Gurvich, A. A., 1950, *Heat-Transfer in the Steam Boiler Furnaces*, Moscow-Leningrad, Gosenergoizdat, p. 176.

Kuznetsov, N. V., Mitor, V. V., Dubovsky, I. E. and Karasin, E. S., 1973, "Heat Calculation of the Boiler Units," Standard Technique, Moscow, Energia, p. 296.

Pomerantsev, V. V., 1986, "Fundamentals of the Combustion Theory," Leningrad, Energoatomizdat, p. 312.

Shatil, A. A. and Danilovtsev, V. N., 1974, "Mass-Transfer in the Steam Boiler Furnaces," *Teploenergetika*, No. 3, pp. 56~59.

Shagalova, S. L. and Shnitser, I. N., 1976, "Combustion of Solid Fuel in the Steam Boiler Furnaces," Leningrad, Energia, p. 176.

Shatil, A. A., 1986, "Furnace Processes and Furnace Devices (Investigation and Calculation)," Leningrad. Energoatomizdat, p. 312.