

THERMOPHYSICAL PROPERTIES OF ASH DEPOSIT ON BOILER HEAT EXCHANGE SURFACES

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ABSTRACT

A brief overview on boiler tubes ash deposit characterization and thermophysical properties of deposits are given.

The structure of an ash deposit on the heat exchange surface of a boiler is usually non-uniform. The thickness of the deposit increases with time and during this process chemical reactions and sintering of ash particles may lead to structural changes. Therefore the thermal conductivity of the ash deposit has to be considered an effective quantity that adjusts energy transfer through the material to a given heat conduction model (for example, planar or cylindrical wall). In this way, an ash deposit may be characterized as a heat-conducting body and compared with other materials.

The radiation flux originating from the ash particle layer and deposit layer is spectral in the region of short wavelengths and the emissivity of the ash particulate layer is lower than the emissivity of a smooth one; in contrast, the selectivity of the slag deposit is negligible. This caused by the relatively good transparency of the layer of fine ash particles, the interaction between particles, and the reflection of radiation into the space.

INTRODUCTION

Ash fouling of heat exchange surfaces in a boiler is a complex phenomenon; it is a result of several physical and chemical processes.

Investigation of ash fouling of boiler tubes has two purposes: to elucidate fouling mechanism and to determine the influence of ash deposit on the heat exchange.

Ash fouling involves transfer of ash particles from the gaseous medium to the boiler tube surface and condensation of flue gas components from the vapor phase on the tube under suitable conditions.

Chemical and mineralogical composition of the ash deposits on a boiler tube usually differs from the composition of fly ash passing through heat exchange surface. This difference is caused by selective deposition of ash particles on the surface, chemical reactions, sintering, and other processes within the deposit layer.

The structure of an ash deposit on the boiler tubes is non-uniform. The thermal conductivity of the ash deposit layer (a factor characterizing heat exchange through the layer according to the Fourier law) has to be considered an effective quantity that adjusts energy transfer through the material to a given heat conduction model (for example, sit, it can cover the surface with a thick layer. The most

planar or cylindrical wall).

The radiation heat exchange between boiler tubes and surrounding medium depends on the thermal radiation properties of the ash deposit.

ASH DEPOSIT

The fouling of heat exchange surfaces of a boiler occurs when ash particles adhere to tube surfaces. An ash deposit is formed when particles of different states present in the flue gas environment are carried onto the tube surface, or when condensation of vapor-phase substances on tubes occurs. During the ash fouling of tubes, a chemical interaction between the ash particles on the ash layer and the flue gas components can take place. By burning of solid fuels the formation of an ash deposit is unavoidable.

Fouling is both a physical and a chemical phenomenon in which physical forces dominate or act together with chemical processes. In the first case, loose deposits are formed. In the second case, the deposit sticks to tube metal. Often physical and chemical processes continue within the deposit layer that has been deposited.

Ash fouling of the heat exchange surface is a multi-stage process: transport and sedimentation of ash particles, condensation or desublimation of vapor present in the gaseous medium, binding of ash particles on the tube surface, and post-transformation processes in the deposit layer (chemical reactions, sintering of particles, etc.).

Several attempts have been made to classify ash deposits, e.g., according to the place of formation (furnace wall tubes, convection heat exchange surface, etc.), chemical composition (sulfate deposit, alkali metal deposit, and so on), and extent of binding (weakly or strongly bound deposit, and so on) [11, 14, 10 and others].

Based on the mechanism of fouling of boiler heat exchange surfaces the classification of ash deposits may be following.

Loose deposit is formed when mechanical forces bind solid particles to the surface with each other. A loose deposit usually quickly stabilizes and attains a shape determined by the gas flow conditions.

Bound-ash deposit is formed when chemical forces bind to the surface and with each other solid particles. Simultaneous condensation and desublimation of vapors can take place. The chemical action of ash particles and the surrounding medium (flue gas) is of great importance. Different densities and porosity can characterize bound-ash deposits. As a result of the unlimited growth of the depo-

common bound-ash deposit is often the sulfate type.

Slag deposit is formed from solid, softening and melting ash particles. Its properties depend on the chemical composition of the ash, temperature conditions, and the composition of the flue gas. Chemical reactions can take place within the deposit. Under suitable conditions, slag deposits grow very quickly and primarily cover the heating surfaces of the furnace (slagging).

Bound-slag deposit forms from melting, softening and solid particles, often accompanied by condensation and desublimation of vapor. The components of such deposit are chemically bound within the deposit layer. Formed deposit can be characterized by different density and porosity and unlimited growth.

The structural scheme of the deposit on boiler heat exchange surfaces are shown in Figure 1 and Figure 2.

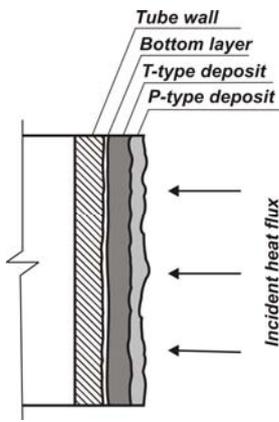


Figure 1. Deposit layers and its structure covering wall tubes.

THERMAL CONDUCTIVITY

It is well known that ash deposits on heat exchange surface tubes of a boiler retard heat exchange from the flue gas to the heated medium and, therefore, inhibit heat transfer in the boiler. To estimate heat exchange efficiency and to elucidate the influence of individual factors on it, one has to know the thermophysical properties of the ash deposit formed on the heat exchange surfaces, the most important ones being thermal conductivity and thermal emissivity.

The structure of a bound-ash deposit on the heat exchange surface of a boiler is non-uniform. The thickness of the deposit increases with time, and, during this process, chemical reactions and sintering of ash particles may lead.

An ash deposit on a heat exchange surface may be examined as a porous material, the effective thermal conductivity of which is determined by the conductivity of the material of its structural framework and the conductivity of the gas in the pores. At higher temperatures, radiant heat transfer inside the material also affects heat exchange in a porous body. Porosity (Π) can be determined on the basis of actual density of the material (ρ) and density of the solid skeleton (ρ_0):

$$\Pi = 1 - \frac{\rho}{\rho_0} \tag{1}$$

On the basis of several studies [1, 5, 10, 11, 16, 13 Table 1. Deposits chemical composition, %.

and others] rough estimates for the thermal conductivity of different types of ash deposits are as follows: loose and weakly bound deposit - 0.1 W/(m·K), bound and sintered deposit - 1 W/(m·K), slag deposit - 2 W/(m·K), and iron-rich slag deposit - 3 W/(m·K).

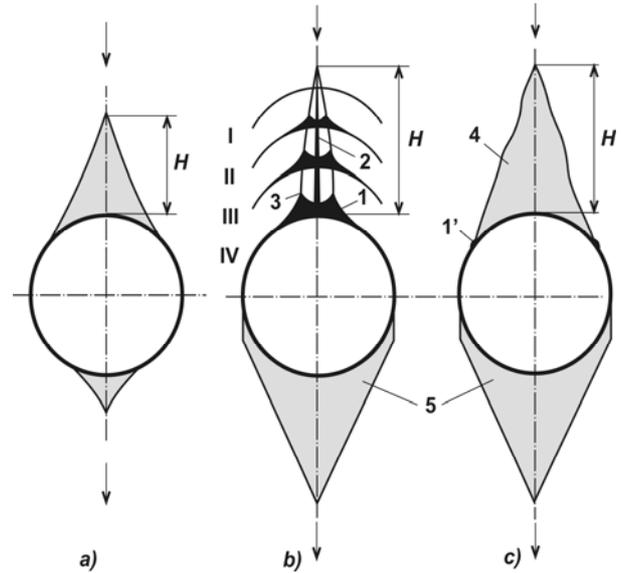


Figure 2. Deposits formed on a transverse-flow tube. a) – loose deposit, b) – bound deposit (hard deposit on the front side and weakly bound on the backside), c) – weakly bound friable deposit on the front and back side. 1 – base, 2 – middle crest, 3 – side crest, 4 – loose crest, 5 – friable deposit on the backside, 1' – thin hard side layer. I-IV – stages of formation of the hard deposit.

Figure 3 shows the relationship of porosity to the thermal conductivity of ash deposits formed on boiler heat exchange surfaces during burning brown coal rich in calcium [5, 16]. The chemical composition of the ash of the combusted coal (mass %): SiO₂ = 32.9, Al₂O₃ = 6.9, Fe₂O₃ = 8.1, CaO = 38.9, MgO = 3.3, Na₂O = 0.6, K₂O = 0.5, SO₃ = 8.4. Samples were taken from the heat exchange surface of an industrial boiler. Chemical composition of investigated samples is given in Table 1.

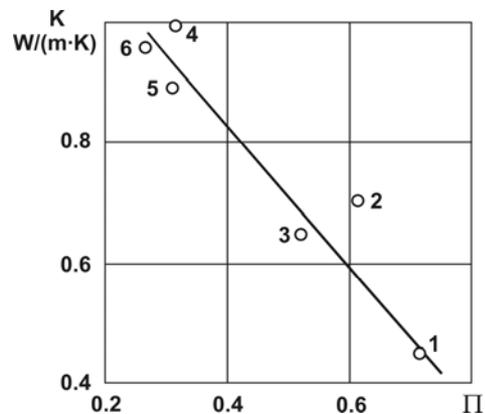


Figure 3. Relationship of thermal conductivity to porosity of the ash deposits; temperature of the deposits is 400 °C.

Sample No	SiO ₂	Fe ₂ O ₃	CaSO ₄	MgSO ₄
1	11.0	17.0	56.6	8.0
2	8.3	7.7	61.4	7.5
3	7.5	31.2	48.6	9.0
4	7.6	24.8	54.0	9.0
5	7.3	14.0	54.4	9.0
6	6.9	14.2	60.1	10.0

All samples were rich in calcium sulfate, and their porosity was 0.2 to 0.8.

Thermal conductivity was between 0.4 and 1.0 W/(m·K). The conductivity decreases quickly with an increase in porosity. It may be concluded that contact between ash particles in the deposit had a substantial influence on thermal conductivity. This is primarily a result of the fact that the conductivity of the solid framework is many times higher than that of the gaseous medium in deposit pores.

The thermal conductivity of all studied samples increased with a rise in temperature. This is supported by results [5, 9, 10, 12 and others].

These results also agree with the values of thermal conductivity of ash deposits formed on heat exchange surfaces of an oil shale boiler [10]. The thermal conductivity of the hard deposits is about 1 W/(m·K); that of weakly bound and loose deposits is usually below 0.2 W/(m·K).

The thermal conductivity of an iron-rich slag deposit, and weakly and hard-bound sulfate deposits an industrial boiler by combustion of Kansk-Achinsk brown coal, was studied [1]. The results of this study are presented on Figure 4. The composition of the deposit was characterized with the sulfate sulfur (as SO₃) content of the sample. The sulfur content is lowest in the slag deposit, which consists mainly of melted minerals and forms at high temperature. An ash deposit rich in sulfate sulfur forms primarily on the basis of calcium oxide. Therefore, the amount of sulfate

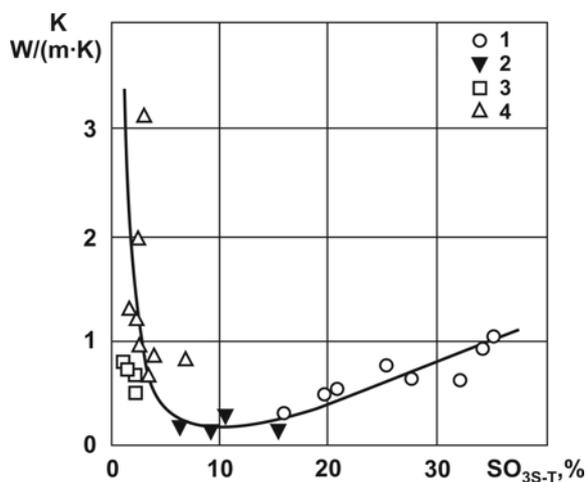


Figure 4. Relationship of thermal conductivity to the content of sulfates (as SO₃) in ash deposits. 1 – sulfate bound deposit, 2 – weakly bound deposit, 3 – slag deposit, 4 – iron-rich deposit. Temperature of the deposit 400 °C.

sulfur in the deposit is an appropriate parameter for characterizing the structure of the deposit.

The data show a rather complex relationship of thermal conductivity to the SO₃ content of the deposit. The high conductivity of the deposit with low SO₃ content is caused by the high density of the material (slag) and the considerable iron content. The conductivity of a porous, weakly bound deposit is lower. An increase in the amount of SO₃ in the deposit makes it denser and, therefore, also increases heat conduction.

The thermal conductivity of a deposit is influenced by its chemical composition (through the ratio of components). The thermal conductivity of a deposit consisting of oxides is considered to be proportional to the mass ratio of the individual oxide's thermal conductivity [12].

The indirect influence of the structure of the ash deposit on thermal conductivity has been studied in [3, 6, 12 and others]. In these studies, the structure of the deposit was influenced by temperature. The thermal conductivity of the sample was determined during the heating and cooling of the ash layer.

Figure 5 shows how temperature influences the thermal conductivity of two ash layers of different values of porosity Π [12]. The composition of this ash (mass %): SiO₂ = 25.5, CaO = 27.3, Fe₂O₃ = 6.8, K₂O + Na₂O = 2.6, SO₃ = 8.6. More than 70 % of the particles were smaller than 5 μ m.

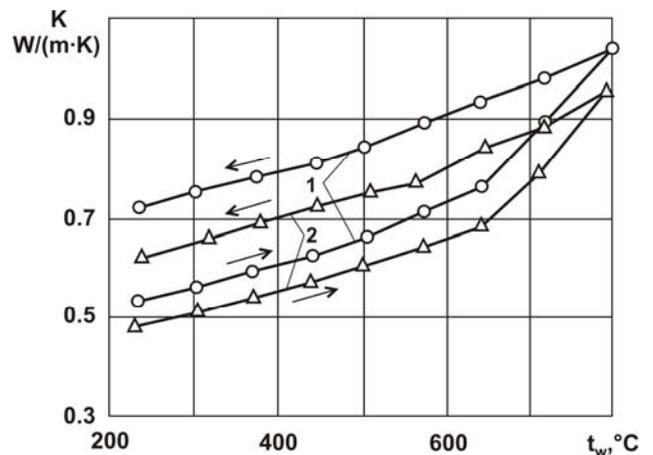


Figure 5. Influence of temperature on thermal conductivity of two ash layers of different initial porosity. 1 – $\Pi = 0.30$, 2 – $\Pi = 0.48$.

Starting from 650 °C (the sintering temperature of the ash), the curve of the relationship of temperature to conductivity rose more steeply. The changes in conductivity during cooling did not coincide with temperature influence during heating. During cooling, the value of thermal conductivity remained higher. The conductivity of a more porous ash layer at a given temperature was lower than that of a less porous bed. The rather complex influence of temperature on conductivity can be explained by the sintering of the ash particles, which improves the contact between particles and enhances the conductivity of the mineral structure of the system.

The influence of temperature on the thermal conductivity of the ash layer can be expressed in two ways. First,

Temperature influences to the conductivity of individual components of the ash (for instance, oxides), which is associated with the composition and structure (crystalline, amorphous) of the substance. Second, temperature influences both the sintering of ash particles and the chemical reactions occurring in the layer. The influence of temperature on the sintering of ash particles and the changes in the extent of contact between them caused by sintering are determined by the chemical and mineralogical composition of the ash. Thermal conductivity increases as sintering intensifies.

It is generally believed [3, 10] that the thermal conductivity of ash deposits is affected primarily by their physical structure (porosity) and not so much by their chemical composition.

As stated previously, at higher temperatures, the share of thermal radiation in the conductivity of a material increases. This issue has been studied in numerous papers [e.g., References 2, 4, 17 and others]. According to data [11], at 500 °C about 7 % of the total thermal conductivity of a solid body of 70 % porosity is associated with radiation. However, with an increase in temperature to 1000 °C, the amount of radiation increases up to 14 %.

The influence of thermal radiation on the thermal conductivity of a solid material (ash deposit) can be expressed in two ways: radiation through a solid transparent medium and radiation through pores. The first case is referred to as phonon conductivity in a solid body with no porosity. The second case is dependent on the porosity of the material (slag deposit) and the particle size (loose deposit). Radiation heat transfer through the pores is more important [17].

THERMAL RADIATION EMISSIVITY

The radiation flux originating from the ash layer in general is spectral.

The spectral emissivity and the absorptivity of ash deposits are affected by wavelength and temperature: $\varepsilon_\lambda = \varepsilon_\lambda(\lambda, T)$. This function is not universal; it is affected by the radiation properties of the solid body (deposit). Since the fouling process of a heat exchange surface is a polyfunctional phenomenon, ash deposits of different compositions and structures also have different radiation characteristics. The integral average emissivity in the wavelength range 0- ∞ is provided by the following formulas:

$$\varepsilon = \frac{\int_0^\infty [\varepsilon(\lambda, T) \cdot I_0(\lambda, T)] d\lambda}{\sigma_0 T^4} \quad (2)$$

The integral average values of emissivity for an ash deposit of given properties depend only on temperature. Many studies have shown that the average emissivity of an ash deposit layer decreases with an increase in temperature; however, the absolute value can vary over a wide range. The emissivity of a clean heat exchange surface (steel covered with oxides) is about 0.8. More detailed investigations have shown that the emissivity of a clean surface depends on the type of steel and the formation conditions of the oxide film covering the tube. The emissivity of

to as low as 0.2 to 0.3. The emissivity of strongly bound and slag deposits can be rather high, 0.80 to 0.95.

Studies of fly ash, ash deposits and slag spectral emissivity by burning of hard coal is presented in [16] and reflects in Figure 6. The figure shows the wavelength relationship of the spectral emissivity of the slag, ash deposit and fly ash layer. One can see that the emissivity of the fly ash and the deposit is selective; in contrast, the selectivity of the slag deposit is negligible. This can be explained by the relatively good transparency of the fine ash particles, the interaction between particles, and the reflection of radiation into the space.

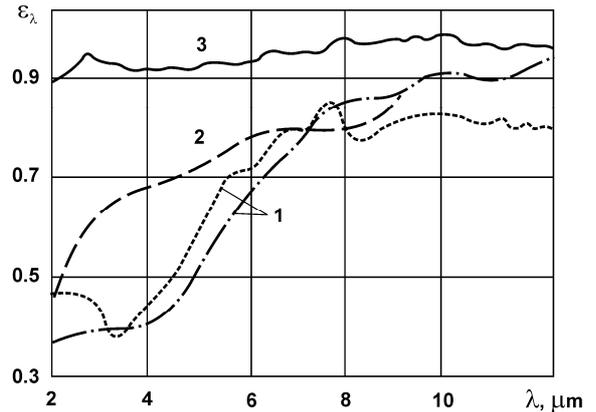


Figure 6. Spectral emissivity of fly ash, ash deposit and slag. 1 – fly ash, 2 – deposit, 3 – slag.

These results effectively explain the low thermal efficiency of the boiler heating surfaces covered with a thin ash deposit layer [8, 10, 15]. Because of low selective emissivity, this type of an ash deposit is highly reflective and has low integral emissivity, which inhibits heat exchange through the deposit layer. This phenomenon was first observed in experiments carried out by Selg [15 and others].

INFLUENCE OF ASH DEPOSITS EMISSIVITY ON HEAT TRANSFER

Ash fouling of heat exchange surfaces is a process during which the thickness and structure of the ash deposit change, so the emissivity of the deposit also changes. The influence of time on emissivity is complex and depends on several factors: grain and chemical composition of the particles deposited onto the surface, the growth rate of the deposit layer, the sintering properties of ash, the chemical reactions taking place in the layer, etc.

Primarily the formation of a white, thin deposit layer of good reflectivity determine the influence of time on the integral emissivity of an ash deposit in the initial stage. This layer usually forms through the transfer of very fine particles of flue gas flow by thermophoresis onto the surface. These particles, as a rule, have formed from compounds containing alkali metals volatilized from the mineral part or from calcium compounds bound with organic matter. The complicated relationship of time to the integral emissivity of such an initial ash deposit is presented on Figure 7 [8, 10] by burning of brown coal with following composition of fly ash (mass %): $\text{SiO}_2 = 33$, $\text{Al}_2\text{O}_3 = 7$,

a thin deposit layer consisting of small particles can drop $\text{Fe}_2\text{O}_3 = 8$, $\text{CaO} = 39$, $\text{MgO} = 3$, $\text{Na}_2\text{O} = 0.6$, $\text{K}_2\text{O} = 0.5$, $\text{SO}_3 = 8$. The results were obtained under the conditions: temperature of metal surface $t_w = 350^\circ\text{C}$, incident heat flux 150 kW/m^2 .

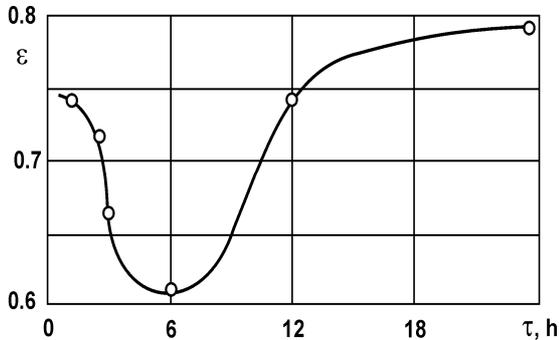


Figure 7. Relationship of time to the integral emissivity of the initial ash deposit.

Initially, the emissivity is equal to the emissivity of a clean surface (oxide film, $\varepsilon \approx 0.75$). Later, the surface becomes covered with a thin layer of particles consisting of crystalline solids, whose thermal emissivity value in the short-wavelength region of spectrum is low and, therefore, reduces integral emissivity. Since a thin layer of the deposit permits the passage of radiation, the oxide layer exerts its influence during the period of an increase in integral emissivity; this influence decreases as the deposit layer thickens. The minimum value of the integral emissivity of a surface covered with the initial deposit corresponds approximately to the emissivity between of the white deposit and oxide layer (~ 0.6). During subsequent thickening of the deposit, as coarser particles are transferred onto the surface, the layer gradually loses its radiation selectivity during chemical reactions within the layer (e.g., sulfating of CaO), and its emissivity approaches the emissivity of a stable deposit covering the heat transfer surface (~ 0.8).

From these findings, generalizations can be assumed about the influence of the ash deposit on radiant heat exchange, schematically presented in Figure 8 [7, 10].

If the incident radiation rate is high ($>150\text{-}200 \text{ kW/m}^2$), the surface quickly becomes covered with ash particles transferred onto the surface in a molten and soft state (in this case, mostly a bound-slag deposit forms). This kind of deposit is characterized by high radiation emissivity, which is approximately equal to the emissivity of the oxidized metal surface. Since the emissivity of the bound-slag deposit increases only slightly over time, the thermal resistance of the deposit R is determined primarily by the heat flux through the deposit layer from the medium onto the surface. This situation is schematically presented on Figure 8,a. The vertical axis represents three parameters characterizing heat exchange: thermal emissivity of the ash deposit (ε_s), thermal resistance of the ash deposit (R) and thermal efficiency of the heat transfer surface (ψ) as the ratio between absorbed by surface heat flux to the incident heat flux. The horizontal axis represents time (τ).

If the incident radiation rate is low ($< 150 \text{ kW/m}^2$), the

surface becomes covered with very fine particles of low emissivity. During the formation of this kind of deposit, the surface emissivity decreases over time; it is affected by the high emissivity of the metal oxide layer and very low emissivity of the dissipated small particles. Since the thermal resistance of a thin deposit layer is small, its thermal conductivity effect on heat absorption is negligible. The decrease in thermal efficiency is caused primarily by a decrease in surface emissivity as average between oxide layer and particles emissivity. As the thickness of the deposit layer grows, both the thermal resistance and emissivity of the deposit increase. After a set time, the emissivity stabilizes at a specific value, and, beyond this time, only thermal resistance of the deposit determines the rate of heat exchange through the surface. This process is schematically presented on Figure 8,b.

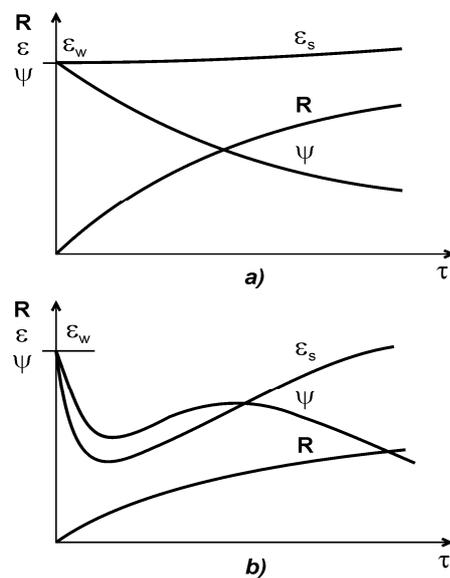


Figure 8. Changes in factors characterizing heat exchange during the formation of ash deposit. a) – high incident radiation, b) – low incident radiation.

SUMMARY

Based on the mechanism of fouling the ash deposits on boiler heat exchange surfaces may be divided on the following four types: loose, bound (weakly and hard bound), slag and bound-slag. The type and properties of deposit on transverse-flow boiler tubes are determined mainly by ash composition, particles size distribution, flue gas velocity and temperature.

On the thermo-physical side an ash deposits may be examined as porous material, the thermal conductivity of which are determined by the conductivity of the solid framework and the conductivity of the gas in the pores. The conductivity decreases quickly with an increase in porosity. The rough estimation of conductivity of loose and weakly bound deposits is $0.1 \text{ W/(m}\cdot\text{K)}$, hard-bound and sintered deposit $1 \text{ W/(m}\cdot\text{K)}$ and slag deposit $2 \text{ W/(m}\cdot\text{K)}$. Conductivity as rule increased a rise in deposit temperature.

eral is spectral. In contrast the selectivity of slag deposit usually is negligible. The emissivity of a thin deposit layer consisting of very small particles can drop to 0.2 – 0.3 but for strongly bound and slag deposits can be 0.80-0.95.

NOMENCLATURE

R – deposit thermal resistance, $\text{m}^2 \cdot \text{K}/\text{W}$

T – temperature, K

I_0 - black body radiation intensity, W/m^2

Π – porosity, dimensionless

ρ – actual density of material, kg/m^3

ρ_0 - density of the solid skeleton of material, kg/m^3

ε – thermal emissivity, dimensionless

λ – wavelength, μm

σ_0 - Stefan-Boltzmann constant, $\text{W}/(\text{m}^2 \cdot \text{K}^4)$

ψ – thermal efficiency of the heat transfer surface, dimensionless

τ – time, h

Subscript

s – deposit surface

w – wall surface

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