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THERMAL AND RADIATIVE PROPERTIES OF ASH DEPOSITS ON HEAT TRANSFER SURFACES OF BOILERS

A review of thermal and radiative properties of ash deposits formed on heat transfer surfaces of the coal- and oil-fired boilers is given in the paper. It is shown that the spectral emissivity, total emissivity, total absorptivity and the effective thermal conductivity of the deposits are greatly influenced by the type of fuel, the way of fuel combustion, the flue gases flow and thermal conditions maintained in the boiler. The radiative properties of deposits seem to depend mostly on the chemical composition and granularity of the ash while thermal properties are primarily influenced by the microstructure of deposits. The ash deposits coming from Polish coal-fired boilers have similar properties to those cited in literature and of another origin. Prediction of radiative and thermal properties of ash deposits seems possible. However, detailed information on ash deposition, its chemical composition and conditions occurring in the boiler during boiler operation is necessary.

INTRODUCTION

The presence of mineral matter in natural fuels influences the performance of many combustion sytems like boilers, gas turbines, MHD generators, coal gasifiers, regenerative heat exchangers [6, 36, 39]. It is also of importance in thermal measuring devices like heat flux gauges [31, 32]. Ash deposition in these systems leads to a substantial decrease of heat transferred between different parts of the systems. It also increases hydraulic resistance to flow of gases, thus affecting mechanical efficiency of turbines and heat exchangers. In MHD generators deposits cause changes in electric and magnetic fields distribution. High temperature corrosion, so important in steam boilers, is also attributed to the presence of melted ash.

This paper is devoted to the presentation of thermal and radiative properties of ashes formed in the coal- or oil-fired boilers. The problem has been studied for years in many countries, especially in those with high number of the coal-fired power plants [8, 9, 13, 16, 17, 39]. Some studies have also been carried out in Poland – in plants where coal, coming from Silesian coal-mines, was burnt [10, 11, 35]. The first section of this paper gives a review of phenomena that occur when deposits are formed on heat transfer surfaces in a boiler. The second one discusses the chemical composition and microstructure of ashes. In the third section, the influence of the fire-side fouling on heat transfer is presented and ash properties important in heat transfer calculation are selected. The next two sections give a thorough analysis on these thermal and radiative properties and are devoted to discussion of factors affecting them. In the last part of the paper the main conclusions referring to the ash properties are presented.

1. FORMATION AND GROWTH OF ASH DEPOSITS ON HEAT TRANSFER SURFACES

When coal or oil is burnt in a boiler the mineral matter, present in the fuel (in an amount reaching even 40-50%), is either deposited as a slag at the bottom of the boiler or, in the form of tiny particles, convected by flue gases to the upper part of the boiler. Some of these particles deposit on cooler surfaces of the combustion chamber or superheaters, some are captured in electrofilters or ejected to the atmosphere. The particles on its way along the boiler are affected by forces of different nature [39]. They are slowed down by gravity and aerodynamic (Stokes) forces, especially in the boundary layers of gases existing at the surfaces. Approach of the particles to these surfaces is helped by thermophoresis and Magnus forces. If the particles have been charged (e.g., by mutual collisions), then their movement to the surface is enhanced by electromagnetic forces (in the presence of electromagnetic fields) or electric forces appearing due to electric induction on the wall (in the absence of electric fields). Being on the surface, the particles are sticking to it due to adhesive forces of electric or Van der Waals origin. Adhesion of the particles is greatly increased by higher roughness of the wall.

The forces acting on particles are dependent on the particle diameter so a selection in the size of particles occurs. Greater particles are deposited earlier – mainly on the front parts of the surfaces, smaller particles form a deposit later and on the rear parts of the surfaces (i.e. superheater tubes) [15]. The particle surface is often melted which helps in better sticking of the particle to the wall. This also leads to the selection in the chemical composition of particles. The particles with lower melting point are deposited earlier in comparison with those of the higher melting point. In the lower part of the combustion chamber processes of growth and melting of the deposit cause irregular dislodgement of the deposit from the chamber walls or flow of a slag down the chamber. In the upper part of the combustion chamber, as well as on the tubes of radiative and convective superheaters, a constant increase of thickness of the deposit is observed [8, 9, 16, 17]. This increase is at first more rapid (after 1 to 2 hours thickness of the deposit usually reaches half a milimeter), then it is slowed down leading to a certain stabilization in the deposit growth. This phenomenon is attributed to a decrease of thermophoresis when difference in gas and deposit outer surface decreases and to an aerodynamic shape of the deposit that has been formed.

Many other factors influence ash deposition [6, 39]. The way the fuel is prepared for combustion and the way it is burnt are some of these factors. The more fuel is pulverized, the higher content of smaller particles in the flue gases and the higher probability of their deposition. The temperature of the flue gases is also of importance. The higher this temperature, the more particles are carried by the gases, and the greater thermo-diffusion forces. The increase in the excess air factor causes the lower concentration of ash particles in the flue gases and hampers deposition. The kind of fuel is another factor that is important during ash deposition. The particles formed in the coal-fired boilers are greater in diameter and have such chemical composition which leads to a centimetre-thick layer of the deposit. The ash deposit, that is formed on tubed-walls of the combustion chamber and on tubes of the radiative superheaters, is tightly bound with the tube surface. The particles formed in the oil-fired boilers are usually smaller. Their deposition on cool surfaces of the boiler mainly occurs on the radiative and convective superheaters. The ash thickness usually attains the thickness of a few millimetres and is easier to remove from the tubes surface.

The higher radiative heat flux in the boiler leads to the surface melting of the deposit which helps in sticking of new particles. If the velocity of the flue gases is increased, then the more ash particles are deposited on the rear surface of the tubes. A decrease of tubes distance in the tube banks of the steam or water heaters causes a decrease in flow rate and enhances ash deposition. This often leads to the formation of slag bridges between the tubes. A mutual interaction of deposits in different parts of the boiler has been observed. An increase of ash thickness in the lower part of the boiler and associated with it higher temperature of the flue gases helps in the sintering and melting of deposits in the upper part of the boiler. The start of the boiler operation (e.g. after periodic surveys) or its switch-off causes a dilatation in tubes length and leads to the deposit fall-off.

A characteristic variation in ash deposit cross-section along the path of flue gases is schematically shown in Fig.1. Primarily, the deposit is formed on the front part of the tubes (Fig.2) and is difficult to remove from the surface. Then, due to changes in the mean diameter, the chemical composition of ash particles and the velocity of flue gases, the shape of the deposit layer is changing. The greatest thickness of the deposit is moving to the rear part of tubes. The deposit is then less tightly bound to the surface. At the water heaters any deposit is hardly visible [35].

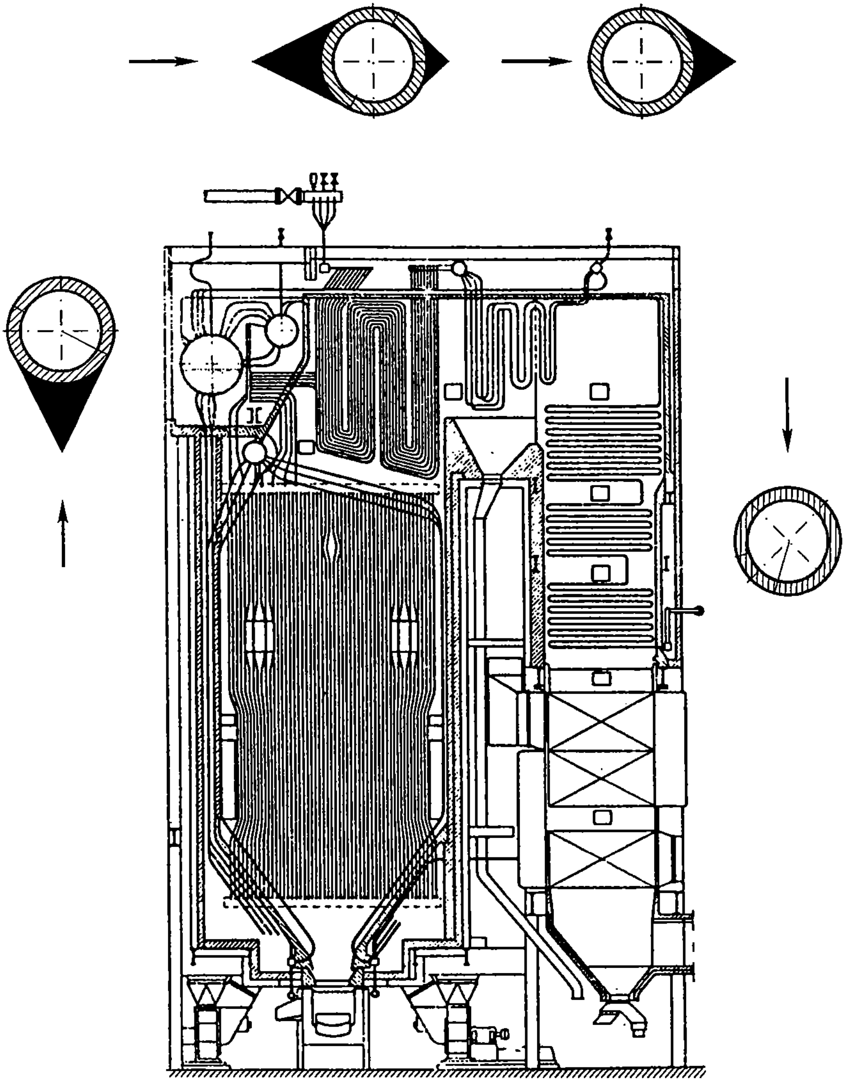

Fig. 1. Characteristic variation of the cross-section of the ash deposit layer on the boiler tubes

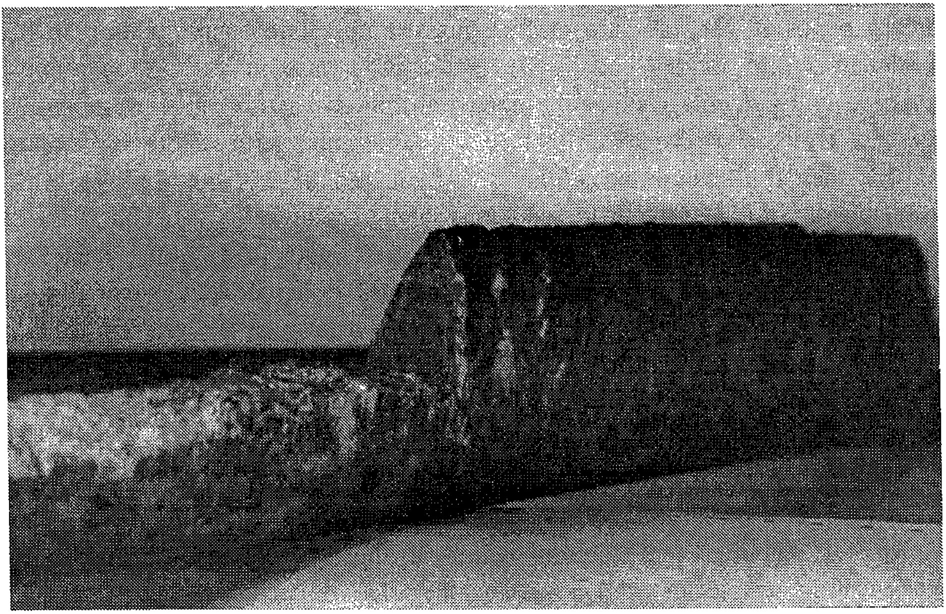

Fig. 2. A characteristic shape of the deposit on a tube surface (from a steam superheater of the boiler from Laziska Power Plant)

2. CHEMICAL COMPOSITION AND MICROSTRUCTURE OF ASH-DEPOSITS

The chemical composition of boiler ashes is greatly influenced by chemical compounds present in the form of minerals in the fuel [6]. Ashes usually contain oxides like SiO_2, Al_2O_3, FeO, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, V_2O_5, SO_3, P_2O_5; carbonates like $NaHCO_3$, K_2CO_3; sulphates Na_2SO_4, K_2SO_4; sulphides like Na_2S, K_2S, FeS, FeS_2 and chlorides like NaCl.

Ashes formed in the coal-fired boilers are abundant in sillica, iron oxides and Al_2O_3 with content of each species reaching several per cent. In the brown coal ashes calcium compounds are also present in a higher amount. Other compounds can be treated as additives. The ashes formed in the oil-fired boilers are much more diverse in chemical composition and contain (besides formerly-mentioned compounds) substantial amounts of potassium, sodium, vanadium and sulphur oxides [19].

Conditions, under which combustion process is carried out in the boiler, are second in importance among factors influencing the chemical composition of ash deposits. The increase of flue gases temperature causes a drop in the amount of some oxides like Fe_2O_3, Na_2O, K_2O, SO_3 in the ash. A relative increase in a percentage of FeO among iron oxides has also been observed. If the gas temperature is lower than the condensation temperature of sulphur oxides, then the amount of sulphates is increased in deposits. Change of an atmosphere (from oxidizing to reducing) in the boiler helps in an increase of FeO content and appearance of sulphides in the ash [42]. If the heat flux absorbed on the outer surface of the ash deposit is higher or the temperature of tube surfaces is raised, then they can cause a drop in the amount of iron oxides by several per cent.

The chemical composition of ash-deposit varies from place to place in the boiler. The maximum values of percentage of the iron oxides are met near burners with a gradual drop observed when moving along a path of the flue gases [16]. It is usually associated with the increase in content of SiO_2, Al_2O_3, TiO_2, SO_3, sulphides and unburnt carbon. In those sites where an amount of NaO, CaO is smaller or SiO_2 is greater, the relative percentage of FeO among iron oxides is increased.

Phase transformations and chemical reactions accompany the ash deposition. At temperatures exceeding 1000°C initially crystalline silica changes into an amorphic form and assumes a shape of spheroidal glassy inclusions [6]. If the ash temperature is of an order of 600-700°C, then a process of sulphatization occurs ($CaO+SO_3 \rightarrow CaSO_4$) [44]. The process can be so intensive that percentage of sulphates in the deposit can be doubled within two weeks from start of the boiler operation. At higher temperatures (greater than 900°C) the opposite process is present which leads to an increase of oxides in the ash-deposit. The amount of iron oxides in the ash is growing due to high temperature corrosion and diffusion. The high temperature corrosion is attributed to the presence of sulphates such as Na_2SO_4, K_2SO_4 in ashes coming from the coal-fired boilers or vanadates like V_2O_5 in the ash-deposit [39]. These compounds are present in ashes in their initial stage of deposition and are believed to form ionic melts in sites where high heat transfer rate occurs. These melts support electrochemical corrosion of metal by forming conduction path to complete galvanic circuit (Fig. 3).

History of the ash deposition has also a profound influence on chemical composition of subsequent ash sublayers [18, 27]. The innermost sublayer, coming from initial stages of ash deposition, is usually rich in FeO, Fe_2O_3, Na_2O, K_2O, $NaHCO_3$, K_2CO_3 and Na_2SO_4. The intermidate sublayer has a high percentage of SiO_2 and unburnt carbon. In the outer sublayer Al_2O_3, MgO, CaO and sulphides are present in the great amount.

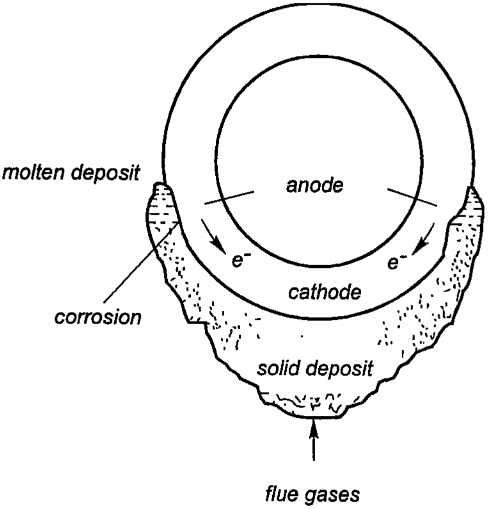

Fig. 3. A scheme explaining mechanism of high temperature corrosion on a tube of a boiler

When chemical composition of ash changes, then the colour of the ash also varies [34]. Ash-deposits, rich in CaO, SiO_2 and Al_2O_3, are white, white-grey, white-blue or white-yellow. These which have growing percentage of iron oxides have colour varying from yellow through yellow-cynamon to cynamon-red. High content of carbon in the ash causes its dark-grey or black colour. There is also a variation of ash colour in cross-section of the ash layer. The inner sublayer is usually red-brown while the outer ones are grey.

At high temperatures the outer surface of ash particles is getting melted. This leads to subsequent processes of softening, sintering and melting of the ash layer. The processes start at lower temperatures if the diameter of an ash particle is smaller. The chemical composition of the ash in these processes is dominant [32, 34]. The sintering and melting temperatures of ash-deposits coming from the coal-fired boilers (having high content of silica) are in the range of 1100-1300°C. Ash deposits coming from the oil-fired boilers have no predominant component and are usually abundant in compounds (like Na_2O, K_2O, V_2O_5) which form low melting point eutectics. Their sintering and melting temperatures cover a broad range from 250°C to 650°C. The presence of some other compounds in the deposit like the iron or calcium oxides causes a decrease while others like Al_2O_3, MgO an increase in ash melting temperature.

Density of the ash-deposit is usually between 60 to 4000 kg/m^3 and porosity in the range of 60-96%. If the deposit density is less than 1000 kg/m^3, it has the unconsolidated, particulate form [34]. Ash deposits coming from the oil-fired boilers are less porous and have density between 1000 kg/m^3 and 2500 kg/m^3 [19]. An increase in percentage of the iron or calcium oxides

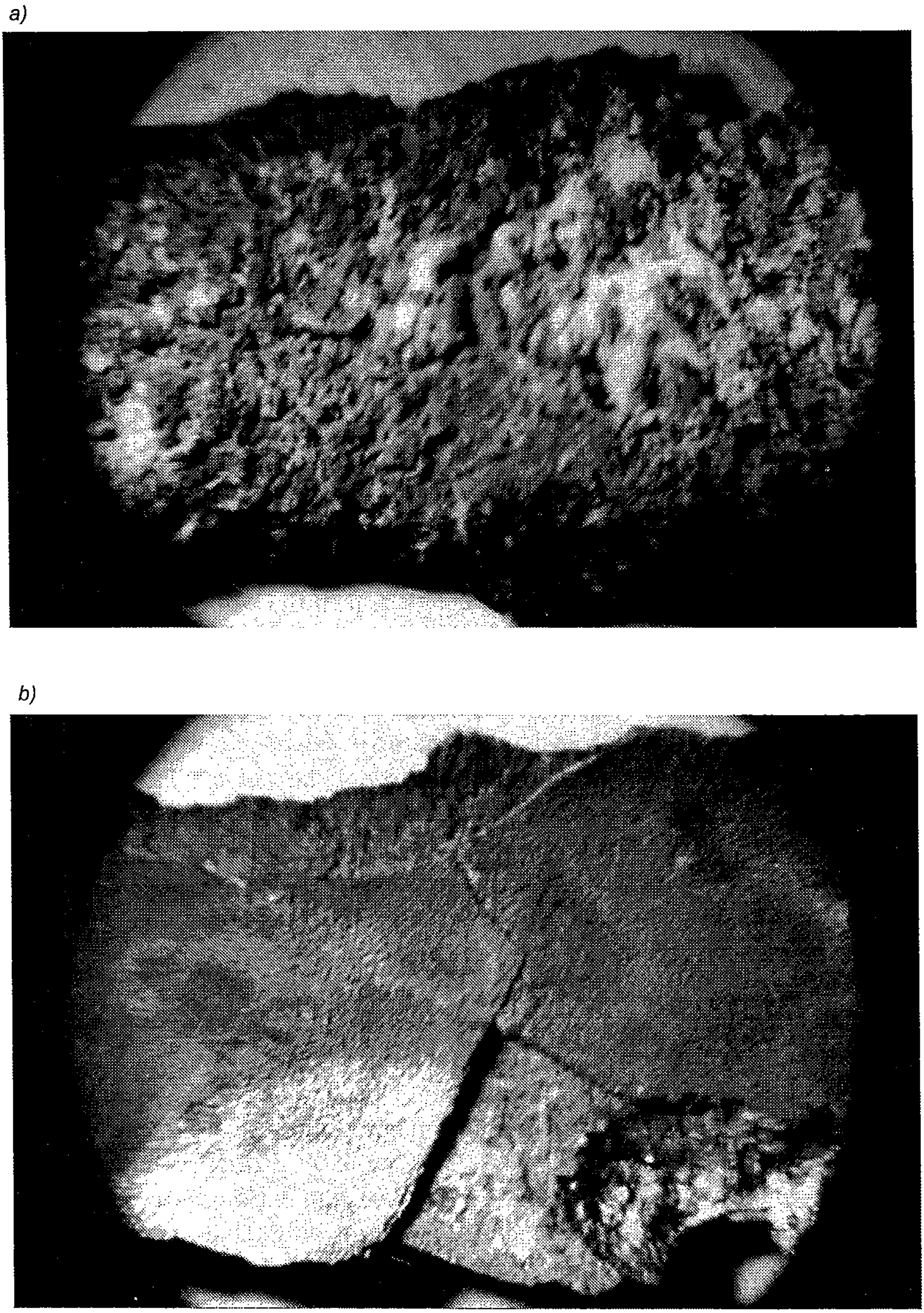

Fig. 4. A fragment of a deposit taken from tubes of the combustion chamber of Lagisza Power Plant: a) external surface of the deposit, b) surface of the deposit adjacent to the tube

leads to the growth of density of the ash-deposit and makes the deposit much more difficult to remove from the heated surface. Due to processes described in the first part of this section the ash-deposit density is varying in the cross-section of the deposit layer. It is higher in the lower part of the boiler and smaller on the superheaters. If the thickness of the ash deposit is increasing with time of the boiler operation, then a process of hardening and increase in the ash layer density is observed.

The ash deposit is characterized by a broad range of particle diameters. They usually vary from parts of a micron to even millimetres [29, 30, 34]. The mean diameter of ash-deposit is getting lower if the temperature of flue gases is increased and is getting greater if the temperature of the heated surface is raised [18]. The microstructure of the ash-deposit is also varying in time. In the first stages of ash deposition a highly dispersive layer of the deposit is initially formed which is subsequently covered by a sintered layer of higher diameter particles. Processes of sublimation and recrystallization of ash-deposit components lead to the growth of the mean diameter of grains in the inner (the nearest to the heated surface) sublayer of the deposit [27]. The outer sublayer is then built of smaller grains (Fig.4). Grains of ashes coming from oil-fired boilers and these which are taken from these places of the coal-fired boilers, where temperature of the flue gases is lower than 800°C, have a crystalline form. Grains of ashes coming from these places of the coal-fired boilers, where temperature of the flue gases exceeds 800°C, have usually spheroidal, amorphous form.

3. INFLUENCE OF ASH-DEPOSITS ON HEAT TRANSFER IN BOILERS

All heat transfer modes: radiation, convection and conduction are present in the boiler. Ash deposition influences each of them. It changes the geometry of the flue gases flow in heat exchangers of the boiler and causes an increase in the gas velocity. The fly-ash suspended in the form of particles in the flue gases changes its radiative heat flux characteristics. The surface of the ash-deposit has different radiative properties than the tube surface such that less thermal radiation is absorbed and less emitted. A layer of the ash deposit forms a thermal resistance to the flow of heat by conduction. Subsequent processes of radiation absorption and emission within deposit sublayers cause the hampering of heat flow by radiation in the deposit. For high optical thickness of the deposit radiative transport of heat is of a diffuse nature while thin ash layers can be semi-transparent to high-temperature radiation. All discussed processes of heat transfer between the flue gases and the heated surface have been schematically shown in Fig. 5.

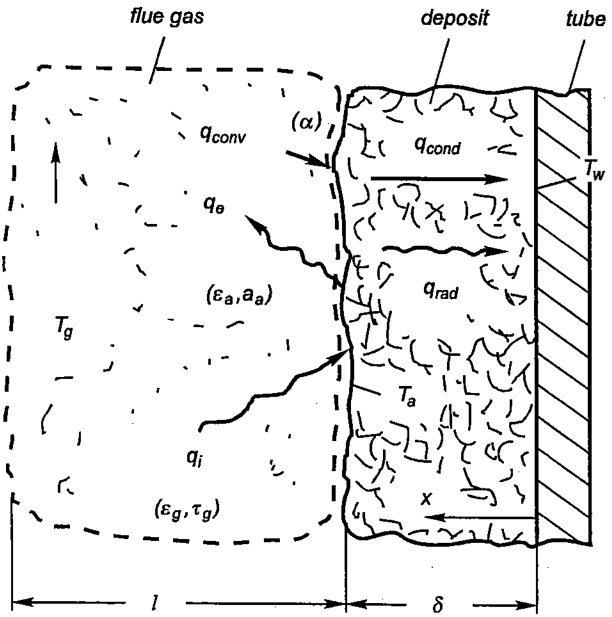

Fig. 5. A scheme of interaction of gas radiation and convection with heat conduction and radiation in the ash-deposit

They can be described by the following formulae:

- heat flux exchanged by convection between the flue gases and a surface of the ash-deposit

$$q_{\mathrm{conv}} = \alpha \left(T_g - T_a\right) \tag{1}$$

  The increase in velocity of the flue gases and changes in the flow pattern due to changes in the shape of the ash-deposit layer cause a small decrease in the mean heat transfer coefficient α. This problem is discussed in [35].

- heat flux exchanged by thermal radiation between the flue gases and the surface of the ash-deposit

$$q_{\mathrm{rad}} = q_i - q_e$$

  where

$$q_i = \varepsilon_g\left(C_0 T_g^4\right) + \tau_g q_e \tag{2}$$

$$q_e = \varepsilon_a\left(C_0 T_a^4\right) + \left(1 - a_a - \tau_a\right) q_i \tag{3}$$

- heat flux transferred by conduction and radiation in a layer of the ash-deposit

$$q_a = q_{\mathrm{rad}} + q_{\mathrm{cond}}$$

where:

$q_{\mathrm{cond}} = -\lambda\, dT/dx$ – conductive component of heat flux,

q_{rad} – radiative component of heat flux.

For high optical thickness of the ash layer the radiative component of the heat flux can be expressed as

$$q_{\mathrm{rad}} = -\lambda_r dT/dx$$

and the effective thermal conductivity of the ash can be introduced

$$q_a = -(\lambda + \lambda_r) dT/dx = \lambda_{\mathrm{ef}}\, dT/dx \tag{4}$$

A close inspection of the above formulae leads to a conclusion that ash affects heat transfer by changing radiative properties of the flue gases like total gases emissivity ε_g and transmittance τ_g to radiation coming from the heated surfaces. The total heat flux is also influenced by the ash-deposit properties: total ash emissivity ε_a, absorptivity a_a, transmittance τ_a and the effective thermal conductivity λ_{ef}. Some of these properties are dependent on the gas temperature T_g (e.g. ε_g) or the deposit temperature T_a (e.g., ε_a, λ_{ef}). The other properties are dependent on both temperatures.

4. RADIATIVE PROPERTIES OF FLY-ASH AND ASH-DEPOSITS

Some studies were carried out on spectral and total radiative properties of fly-ash and ash-deposits. They embraced both theoretical estimations and measurements of transmittance, reflectivity and emissivity of the ash samples either taken from different sites of the boiler or artificially prepared from chemical components met in real ashes. Experimental values of total radiative properties were usually obtained with the help of different kind of radiometers. For spectral properties mesurements either Perkin-Elmer spectrophotometers or radiometers with bandpass filters were applied.

4.1. The optical constants of the ash

In order to understand the influence of many factors on radiative properties of the ash-deposits, to estimate the effect of ash on the radiative properties of the flue-gases and to predict the radiative properties of the ash-deposit, it is neccesary to review the optical constants n_Λ and κ_Λ of the substances which are components of material the ash particles are made of. These optical constants form the real and imaginary part of the complex refractive index of a material

$m_\Lambda = n_\Lambda - j\kappa_\Lambda$ ($j = \sqrt{-1}$). The real part n_Λ of the complex refractive index can be related, for example, to bending of light beam when it travels from one material into another. The imaginary part κ_Λ of the complex refractive index characterizes the absorption ability of the material. The complex refractive index is wavelength-dependent [5, 7]. The wavelength Λ of interest for radiative heat-transfer calculations lies in the range from 1 to 12 μm. The optical constants for several pure oxides, being components of the ash particle material, are shown in Fig. 6. It can be noticed that the real part of the complex refractive index does not vary appreciably in the considered wavelength range. For most oxides it is close to 1.5. Quite different behaviour is observed for the imaginary part of the complex refractive index. Its values are highly wavelength-dependent and change many orders of magnitude. Generally, very small values of κ_Λ are found for the left limit of the considered range of wavelengths but κ_Λ increases with wavelength. The low oxidized iron oxide FeO has high values (reaching 10^{-3}) of κ_Λ at relatively short wavelengths (less than about 4 μm). Similar behaviour has been found for titanium oxide. Even higher values of the imaginary part of the refractive index have been measured for coal (of an order of 0.5) [5].

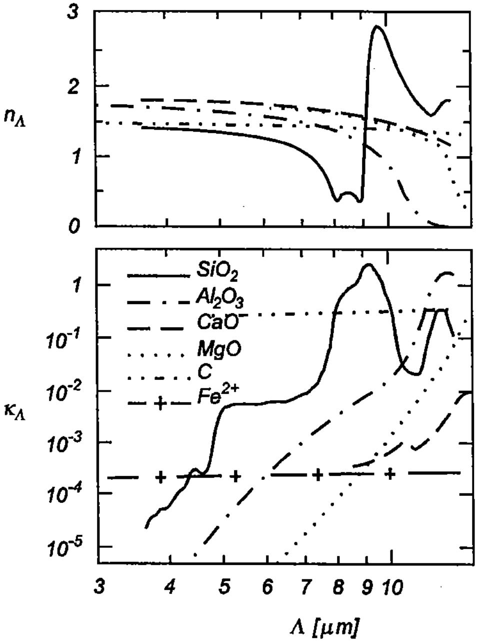

Fig. 6. Variation of the real n_Λ and the imaginary κ_Λ part of the complex refractive index with the change of wavelength of radiation for some constituents of ash [14]

The ash particles are a mixture of different chemical compounds and can be treated as impure aluminosilicate glasses so their optical constants (mainly

κ_Λ) are very sensitive to chemical composition [14]. In Fig.7 it is shown that presence of a few percent of iron oxides in the ash changes its imaginary part κ_Λ of the complex refractive index drastically in the short wavelength limit.

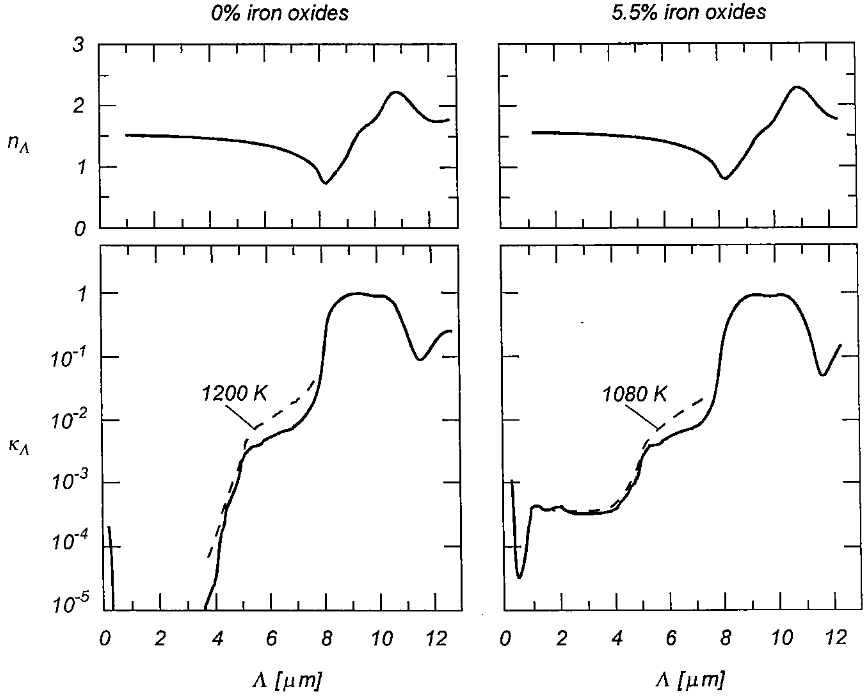

Fig. 7. Variation of the real n_Λ and imaginary κ_Λ part of the complex refractive index with the change of wavelength of radiation for a mixture of ash constituents with different fraction of iron oxides [15]

4.2. Spectral absorption and scattering coefficients

When ash appears in the form of particles (as is usually the case) than another process (besides absorption or emission of radiation) occurs. The particles scatter radiation. The interaction of a cloud of particles with radiation can be described by the absorption coefficient σ_a, scattering coefficient σ_s and the mean phase function $p(\omega' \rightarrow \omega)$. The latter function is connected with the directoral distribution of the scattered radiation. All of the mentioned coefficients are dependent on wavelength Λ, the complex refractive index m of the material, on the particle shape and diameter and on the volume fraction of particles in the medium. If the scattering can be treated as independent (very small volume fraction of the particles), then these coefficients and the phase function can be calculated using the Mie theory. The Mie theory is based on the interaction of electromagnetic radiation with a single particle with a proper averaging carried out for polydispersions [7]. If the volume fraction of particles is high (as in the deposit), then the proper way of estimation of these coefficients and the phase function must take into account dependent scattering by ash particles. However, the theory of dependent scattering is not developed to a reliable extent yet.

4.3. Emissivity and transmittance of the fly-ash in the flue gases

If the radiative properties σ_a, σ_s and $p(\omega' \to \omega)$ as well as the geometry of the radiating flue gases is known (i.e. their shape and dimensions), then it is possible to compute the spectral hemispherical emissivity $\varepsilon_{g\Lambda}$ and the spectral diffuse transmittance $\tau_{g\Lambda}$ of the gas layer. Calculations of this kind are usually carried out by solving the radiative transport equation for the ash loaded gas. In the simpler approach, the emissivity and the transmittance of the gas can be obtained from the following formula

$$\varepsilon_{g\Lambda} = 1 - \tau_{g\Lambda} = 1 - \exp\left(-\sigma_{e\Lambda} l\right) \tag{5}$$

where the spectral extinction coefficient is defined as $\sigma_{e\Lambda} = \sigma_{a\Lambda} + \sigma_{s\Lambda}$ and the geometric mean beam length l can be calculated from expression

$$l = 0.9\left(4 V_g / A_g\right)$$

valid in the optically-thin, non-scattering limit. The volume V_g of the radiating gas is decreased while and the irradiated surface A_g is increased where it is influenced by the presence of the ash-deposit. Dependence of l on the deposit shape and parameters characterizing tube bundle are discussed, in detail, in [35].

Radiation absorption, transmission and emission of the fly-ash-loaded flue gases are influenced not only by the ash particles but also by such gas components as H_2O and CO_2. The spectral emissivity and transmittance of H_2O/CO_2 and the ash/H_2O/CO_2 mixtures, taken from [15], are shown in Fig. 8. For wavelengths smaller than 2.4 μm, both the ash and the molecular gases have fairly low emissivity, and none of them dominates the combined emissivity. The region from 2.4 to 4.8 μm is dominated by the strong bands of H_2O and CO_2 at 2.7 μm, and by the strong band of CO_2 at 4.2 μm. The presence of the fly-ash results in a decrease of the spectral emissivity at the peaks of these bands. This is due to the ash particles scattering of radiation emitted by the gases. The largest effect of the fly-ash on the spectral emissivity occurs in the long wavelength region ($\Lambda > 5 \mu m$). The molecular gases exhibit a region of relatively low emissivity near 10 μm, where the ash has the highest emissivity. The fly-ash particles at these wavelengths are thus the dominant emitter.

The presence of the ash greatly alters the transmittance of the flue gases layer as compared with the transmittance of the flue gases containing only H_2O and CO_2. With only the molecular combustion products present, the layer has regions of high transparency between the gas bands. With the ash, however, the transmittance is low at all wavelengths, due to scattering by the ash particles. The presence of the ash-loaded gas in cool layers near heated surfaces may thus significantly impede the transport of the hot gas radiation to the walls.

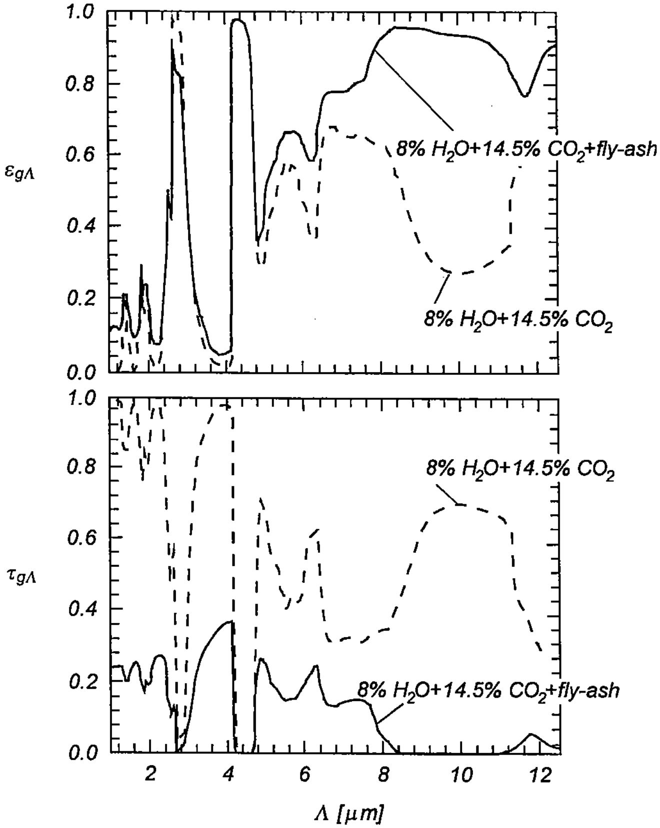

Fig. 8. Dependence of the spectral emissivity $\varepsilon_{g\Lambda}$ and transmittance $\tau_{g\Lambda}$ of the flue gases with and without fly-ash on the wavelength Λ [15]

4.4. Spectral and total emissivities of the ash-deposit

A significant feature of dielectrics (which include ash-deposits) is a region of low spectral emissivity at short wavelengths (up to 2 or 3 μm) followed by a region of high emissivity at longer wavelengths, which is usually strongly banded. This feature corresponds to a general behaviour of the spectral extinction coefficient $\sigma_{e\Lambda}$ of the ash components. However, the chemical make-up of a deposit causes some modification in details of variation of $\varepsilon_{a\Lambda}$ versus wavelength [21, 40, 42-44]. These modifications are consistent with behaviour of the imaginary part of the complex refrective index (Fig.6). Thus, an increase in SiO_2 and decrease in Al_2O_3 or MgO content causes a few per cent increase in the spectral emissivity for wavelengths in the range 4-6 μm. If an amount of the iron oxides (especially FeO in comparison to others) is growing, then a substantial increase in $\varepsilon_{a\Lambda}$ of the deposit is observed which manifests itself in the wavelength region 1.5-3 μm. The process of sulphatization leads to the disappearance of the calcium oxide and causes the increase in $\varepsilon_{a\Lambda}$. The high content of SO_3 and high temperature of the flue gases help in a deposition of the ash layer that is characterized by the high value of the spectral emissivity. Transformation of the silica, present in the ash, from the crystalline to amorphous form results in a decrease of $\varepsilon_{a\Lambda}$. The spectral emissivity of the ash deposit is very sensitive to the mean diameter of the ash particles. Greater particles make $\varepsilon_{a\Lambda}$ higher.

In general, variation of the deposit composition and microstructure along flow of the flue gases causes an increase of the spectral emissivity of the deposit up the height of the boiler. Due to the high density, in comparison with the fly-ash, the deposit is practically non-transparent to thermal radiation. The ash-deposit is already totally opaque for a layer exceeding 0.7 mm.

The total emissivity of the ash-deposit can easily be calculated from the spectral emissivity using the following formula

$$\varepsilon_a = \int_0^\infty \varepsilon_{a\Lambda}(T_a,\Lambda)\, e_0(T_a,\Lambda)\, d\Lambda \Big/ \left(C_0 T_a^4\right) \tag{6}$$

where

e_0 – spectral black body flux density (Planck's function),

C_0 – Stefan-Boltzmann constant.

Similarly to the spectral emissivity, the total emissivity of the ash-deposit is also increasing with the diameter of ash particles [4, 42]. It is also decreasing with the increase of the ash temperature T_a, because the growth of T_a causes a shift of ash emission to shorter wavelengths at which the spectral emissivity is lower. This fact has been confirmed by measurements made on the samples of the sintered ash coming from Polish coal-fired boilers (Fig.9a).

The chemical composition of the ash-deposit has the greatest influence on ε_a at lower temperatures. Ash-deposits coming from the oil-fired furnaces have usually higher values of the total emissivity (Fig. 9b). This is due to a bigger dimension of their particles and their crystalline form. Transformation of microstructure of ash-deposits caused by processes of softening, sintering and melting lead to the observable increase of the total emissivity. Variation of ε_a for ashes, due to transformation of their microstructure, is greater for ashes coming from the coal-fired furnaces than from the oil-fired ones. The silica content is mainly responsible for this behaviour. The increase in the percentage of SiO_2 leads to the shift of abrupt changes in the total emissivity to higher temperatures [32]. The increase in the content of colour agents (like iron oxides and soot) in the ash-deposit causes an observable growth in the value of the total emissivity (due to their intensive interaction with radiation) [29].

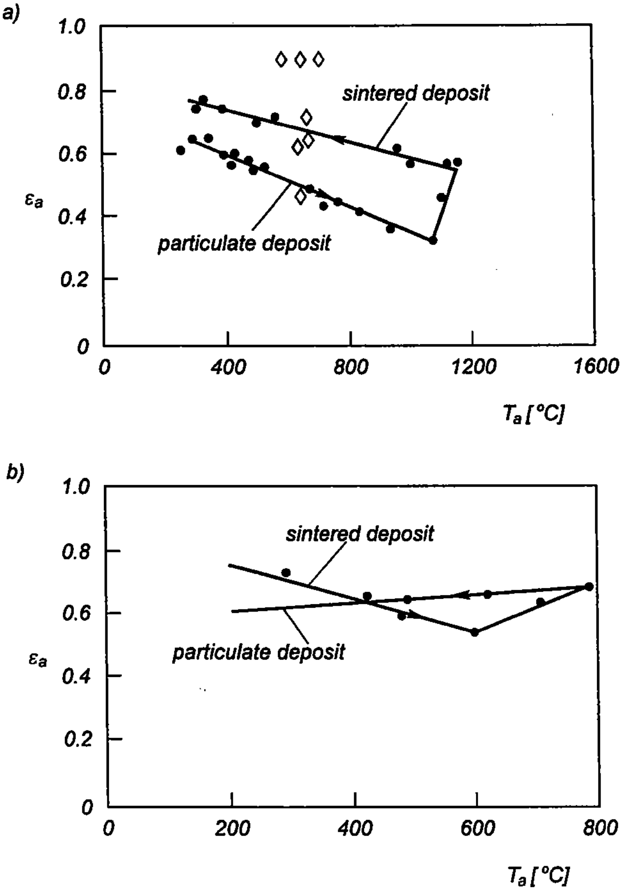

Fig. 9. Variation of the total emissivity of a deposit coming from the coal- (a) and the oil-fired boilers (b) with temperature of the ash surface: ● experimental values cited in literature [31], ◊ for some ash-deposits from Polish coal-fired boilers

4.5. Total absorptivity of the ash-deposit

The total absorptivity of the ash-deposit depends on both its own temperature T_a and the temperature T_g of the radiative source (flame or the flue gases). It can be essentially calculated from the spectral emissivity of the deposit according to the formula

$$a_a = \int_0^\infty \varepsilon_{a\Lambda}(T_a, \Lambda)\, e_0(T_g, \Lambda)\, d\Lambda \Big/ \left(C_0 T_g^4\right) \tag{7}$$

In general, as for the total emissivity, the total absorptivity decreases with the increase of the source temperatures [1, 40]. The reason for it is again the movement of the region of maximum energy of Planck's function towards shorter wavelengths. Below the sintering temperature the absorptivity increases with increasing ash temperature (Fig.10). The rate of increase is dependent on the iron content of the ash and leads to the higher absorptivity of the deposit having more iron oxides. The total absorptivity of the ash-deposit is smaller than its total emissivity. For a typical boiler conditions: T_g = 1700 - 1900 K, T_a = 700 - 1000 K the ash absorptivity can be as low as 0.3 [40].

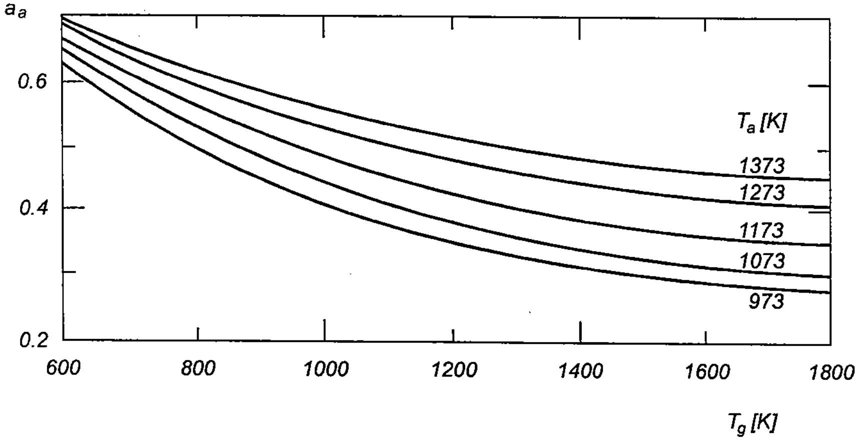

Fig. 10. Dependence of total absorptivity of the ash-deposit on the temperature T_g of the radiation source (treated as the black body) and temperature T_a of the ash surface

The curvature of the steam tubes and the roughness of the deposit will cause higher „effective" total absorptivity and emissivity.

5. THERMAL PROPERTIES OF ASH-DEPOSITS

Several investigations were carried out on the effective thermal conductivity λ_{ef} of the ash-deposit in unsintered, sintered and melted form. For measurements different kinds of steady-state conduction, absolute methods were usually used. The known measurements on the specific heat c_p (using scanning differential calorimeters) and thermal diffusivity a (obtained with laser pulse method) are sparse and refer to a slag (molten ash deposit).

5.1. The effective thermal conductivity of the deposit

The ash deposits, due to their high porosity and granular structure, are typical heterogeneous materials. Their effective thermal conductivity λ_{ef} lies in the range 0.01 - 2 W/(m·K) and is greatly influenced by the temperature of the deposit. A characteristic variation of λ_{ef} with temperature is presented in Fig. 11. The effective thermal conductivity of ash deposit increases with temperature, and once sintering begins, this increase is much more rapid than in the completely fused state, so λ_{ef} can be an order of magnitude higher than at the start of sintering [3]. This behaviour is attributed to the variation in microstructure of the deposit. Processes of sintering and melting lead to the increase of the mean particle size and the decrease in the ash porosity. The deposits of larger mean particle size have higher thermal conductivity. For the lowest mean particle sizes with dimension of pores less than 0.5 μm the effective thermal conductivity of the particulate ash-deposit is of the same order as, or less than, that of air at the same temperature [4]. This phenomenon is explained to be an effect of Knudsen conduction in the pores whose dimensions are

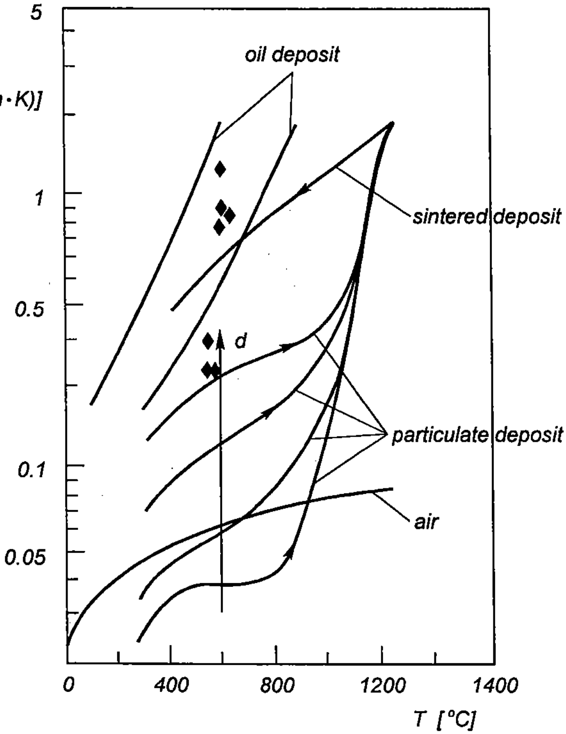

Fig. 11. Dependence of the effective thermal conductivity of the ash-deposit on temperature and the grain size *d* for deposits coming from the coal- and oil-fired boilers [32]: ♦ – some results for ash-deposits coming from Polish coal-fired boilers

comparable with the mean free path of gas molecules. This mechanism is less effective than the bulk collision mechanism for normal conduction.

The effective thermal conductivity of the ash-deposit increases with the increase of ash density. It can be, for example, observed in Fig. 12 which presents variation of the effective thermal conductivity in the cross-section of a layer of the sintered deposit.

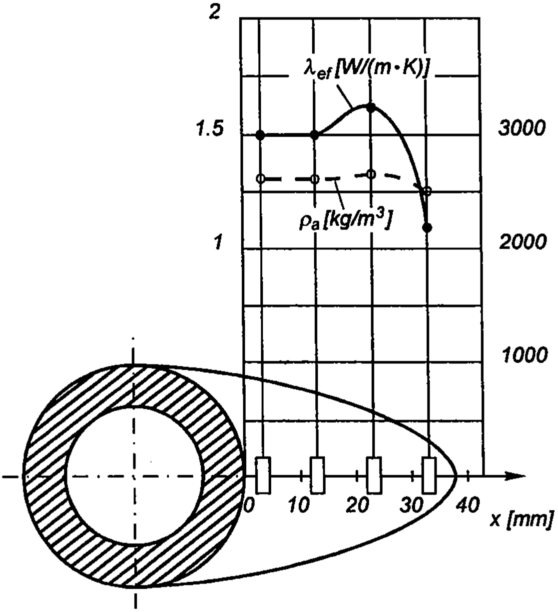

Fig. 12. Variation of the effective thermal conductivity λ_{ef} and density ρ_a of the ash-deposits (coming from Polish coal-fired boilers) across a layer of the deposit (at temperature 20°C)

During process of ash deposition its microstructure changes. Primary layer, deposited in the first stage of ash formation, has the high porosity (75-90%) and is fine-grained. Its conductivity is equal to 0.08-0.3 W/(m·K) and thus it presents a high resistance to heat flow [27]. Temperature drop across this primary layer, several microns thick, is of an order of 200-500 K. Temperature conditions occurring in this layer result in the sublimation of the high volatile components, their subsequent condensation and recrystallization. These processes lead, on one hand, to the reduction of the primary layer thickness, while on the other hand, they result in a buildup of an ash layer on the metal surface that has big-sized grains and better contact area between them (Fig.4). Thus, after some time since the start of ash deposition, the effective thermal conductivity of the layer adhearing to the metal surface is always higher and, depending on sintering and granularity degree, varies in the range 0.2-1.7 W/(m·K).

The chemical composition of the unsintered, particulate ash is of secondary importance compared with its thermal history of formation in determining the

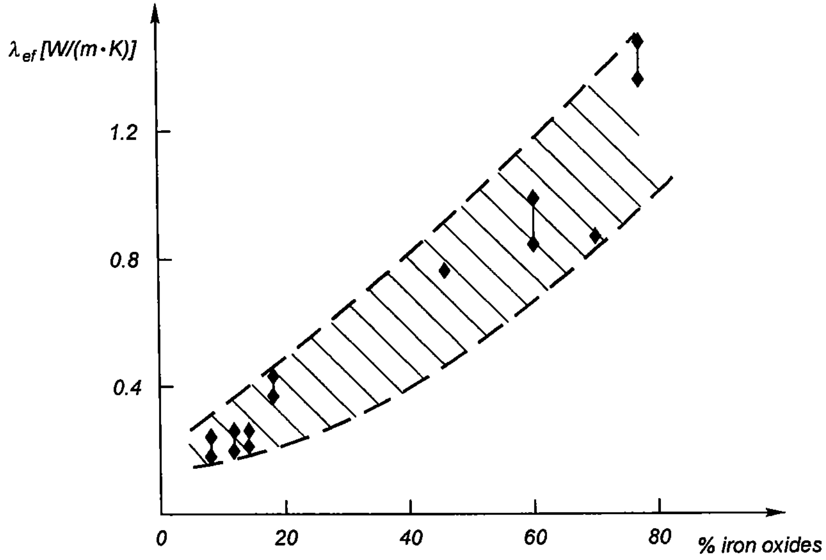

Fig. 13. Variation of the effective thermal conductivity of the ash-deposits (coming from Polish coal-fired boilers) with content of iron oxides (at temperature 500-600°C)

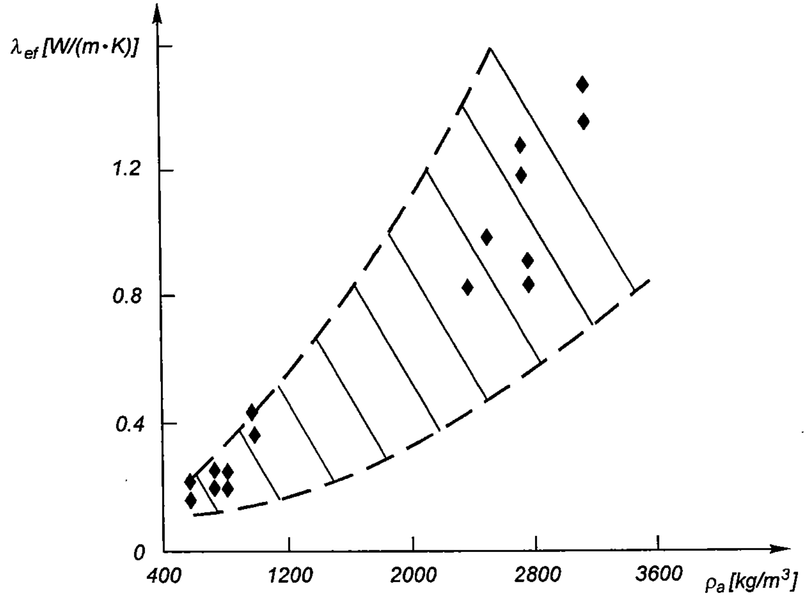

Fig. 14. Variation of the effective thermal conductivity of the ash-deposits (coming from Polish coal-fired boilers) with the ash density ρ_a (at temperature 500-600°C)

effective thermal conductivity [31]. Only high percentage of coloured agents, like unburnt carbon and iron oxides (with enhanced thermal radiation absorption), are assumed to influence λ_{ef} considerably (Fig. 13). It should be, however, kept in mind that the increase in content of iron oxides leads to a higher density of the deposit, which may be the main reason for the increase of the effective thermal conductivity (Fig. 14). The insensitivity of λ_{ef} to the chemical composition is valid for temperatures before the onset of sintering. As noted in section 2, the sintering temperature is greatly affected by the chemical composition of the ash. The effective thermal conductivity of deposits coming from the oil-fired furnaces is usually higher than those which deposited in the coal-fired boilers. This difference is put down to the fact that the oil-ash deposits are of polycrystalline nature with fairly large original grains which have good contact with one another [19].

5.2. Specific heat and thermal diffusivity of the slag

Specific heat c_p of slags formed by melting of the ash-deposit typical for dielectric materials and of an order of 1 kJ/(kg·K). For slags having a high content of slilica and at temperatures above 900 K a phase transition from crystalline to amorphous form of glass occurs. As the specific heat of the crystalline form is less than that of the supercooled liquid, a sudden increase (of an order of 20-30 %) in c_p is observed.

The thermal diffusivity a of slags is of an order of $4.5 \cdot 10^{-7}$ m^2/s. On the onset of glass transition a decrease in a is found (followed by an increase) due to higher values of c_p for the supercooled liquid than for the crystalline form of glass. The varying amount of crystallinity in the slag during process of this phase transition leads to a difference of behaviour of the slag having a different chemical composition. Due to processes of sintering, melting, and changes in the slag microstructure the thermal diffusivity of the slag shows similar thermal history behaviour as the effective thermal conductivity.

CONCLUSIONS

Thermal and radiative properties of the fly-ash and ash-deposit were discussed in the paper. It was shown that they depend on the chemical composition and microstructure of the ash. The history of formation of the ash-deposit, chemical and physical processes (phase transformation, variation in microstructure) occurring in the ashes during operation of the boiler have predominant influence on these properties and their variation in time. Dependence of the thermal and radiative properties of ashes on different factors can be qualitatively understood by considering such basic properties as the complex index of refraction of the main components of the ash-deposit as well as parameters describing microstructure such as porosity, distribution of grain sizes, etc. Properties of the ash deposits coming from Polish coal-fired boilers have similar values and show essentially the same dependence on different factors as the ashes cited in literature.

Formation of the deposit has a profound influence on heat transfer in the boiler especially in the first stages of ash deposition. Already after a few hours since beginning of the boiler operation the deposit layer can reduce heat transfer by almost a half due to a considerable resistance that it offers to the heat flux [16, 20]. The ash layer quickly builds up and attains a thickness of cm in the coal-fired boilers. The deposits thus require a regular dislodgement either by air- or water blowing, or application of vibrations in order to maintain acceptable boiler performance. Use of some additives to the fuel such as MgO can help to make the deposit more easily removable from the tubes surface, however, one should be aware that a greater amount of ash-deposit is created at the same time.

Forecast of thermal and radiative properties of ash-deposits is difficult due to the complex interaction of different factors such as conditions of the flue gases flow, heat transfer in the boiler, chemical reactions, phase and microstructure transformations in the ash-deposit. At present, measurement of the deposit properties directly on the ash samples seem more reliable. Nevertheless, attempts to predict these properties and studies carried out on mechanism of the ash formation on the heated surfaces, if successful, can help in better design and operation of the boilers.

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WŁAŚCIWOŚCI CIEPLNE I RADIACYJNE OSADÓW POWIERZCHNI OGRZEWALNYCH URZĄDZEŃ KOTŁOWYCH

Streszczenie

W pracy dokonano przeglądu właściwości cieplnych i radiacyjnych osadów powstających na powierzchniach ogrzewalnych urządzeń kotłowych powstałych przy spalaniu paliw stałych i ciekłych. Wykazano, że właściwości te (emisyjność, absorpcyjność, efektywna przewodność cieplna) zależą od rodzaju i stopnia rozdrobnienia spalanego w kotle paliwa, sposobu spalania, sposobu przepływu spalin oraz warunków termicznych panujących w kotle. Właściwości radiacyjne osadów, poza temperaturą, zależą głównie od składu chemicznego i wielkości ziarn osadu, natomiast efektywna przewodność cieplna osadu zależy silnie od struktury osadu (porowatość, wielkość ziarn osadu, gęstość). Wyniki pomiarów przewodności cieplnej i emisyjności wybranych próbek osadów pobranych z powierzchni rur polskich kotłów energetycznych świadczą o tym, że osady te mają podobne właściwości do cytowanych w literaturze. Wydaje się, że możliwe jest przewidywanie właściwości osadów kotłowych, ale pod warunkiem że znany będzie sposób osadzania się zanieczyszczeń, ich skład chemiczny i warunki spalania paliwa w kotle.

ТЕРМИЧЕСКИЕ И РАДИАЦИОННЫЕ СВОЙСТВА ЗОЛОВЫХ ОТЛОЖЕНИЙ НА ПОВЕРХНОСТИ НАГРЕВА КОТЕЛЬНЫХ АГРЕГАТОВ

Краткое содержание

В работе проведен обзор термических и радиационных свойств отложений, возникших на поверхностях нагрева котельных топок во время сжигания твердого и жидкого топлива. Установлено, что эти свойства (эмиссионная и поглощательная способность, эффективная теплопроводность) зависят от сжигаемого в котле топлива и степени его раздробления, способа проведения сжигания, течения топочных газов и термических условий в топке.

На радиационные свойства отложений влияют, кроме температуры, химический состав золы и величина частиц. Эффективная теплопроводность золы в большой степени зависит от ее микроструктуры (пористость, величина частиц, удельный вес золы). Результаты измерений теплопроводности и эмиссионной способности образов золовых отложений, собранных с поверхности труб польских энергетических топок свидетельствуют, что их свойства похожи на приведенные в литературе. Предусмотрение свойств золовых отложений возможно при условии, что известен способ образования золы, ее химический состав и способ сжигания топлива в котле.