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Chapter 6

Effects of Ash Deposition and Slagging on Heat Transfer

Chapter Outline

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6.1 ASH DEPOSITION AND SLAGGING PROCESSES AND CHARACTERISTICS [15]

6.1.1 Deposition and Slagging

For boilers that use solid fuel, deposition on the heating surface, such as in pulverized coal furnaces, in grate-fired furnaces, or on the suspended heating surface of CFB boilers, is inevitable. Deposition and slagging cause the thermal resistance from the flame to the working medium to increase, which decreases the absorbed heat of the heating surface and reduces the boiler’s thermal efficiency.

Deposition is characterized by loose ash particles adhering to the heating surface. Only when suspended ash particles have already solidified before touching the heating surface, can loose deposition form. In contrast to deposition,

slagging is characterized by a tight ash layer adhering to the heating surface. Generally, melting or viscous ash particles attacking the heating surface will form slagging rather than deposition.

Ash layers form through some of the following ways.

1. The finest particles in the vicinity of the water wall surface move to the sub-layer of the gas boundary through molecular diffusion, turbulence diffusion, or Brownian movement.
2. Alkali sulfates, chlorides, and hydroxide in gas condense on the surface of the water wall.
3. Large particles move, being carried by the gas flow.
4. High-temperature electrophoresis.
5. Static electricity between fly ash particles and the water wall.
6. Softening and melting particles form sedimentary layers on the surface of the water wall.

Deposition and slagging have clear differences, but are closely related. Deposition forms when ash accumulates on the heating surface at temperatures lower than the ash fusion point, and slagging forms when melting ash accumulates on the heating surface. Slagging is related to the composition, fusion temperature, and surface temperature of ash particles that transfer to the surface under various types of force, usually occurring on the radiation heating surface of the high-temperature zone. Severe deposition or slagging worsens the heat transfer conditions, influencing output and hydrodynamic performance to the point where an accident may occur. So it is very important to avoid deposition and slagging.

Slagging in a pulverized coal furnace usually occurs due to fusion deposition, which is usually related to the transfer conditions of melting or viscous ash particles in the flue gas. When the gas cools down, vaporized matter in the high-temperature area condenses, potentially making these elements accumulate as fusion ash on the furnace wall and forming a tight ash layer.

Slagging and deposition on the boiler heating surface are related to not only the fusion point and composition of the fuel and its ash, but also the design parameters of the boiler such as combustor layout, furnace thermal load, furnace outlet temperature, superheater location, gas velocity/temperature, steam temperature, tube wall temperature, and pitch and arrangement of the heating surface. Slagging and deposition are affected by operating conditions such as load changes, fuel changes, the flow field in the furnace, the multiphase properties of fly ash, the heat transfer process in the furnace, installation of the soot blower and its blowing frequency, the excess air coefficient, and the combustion adjustment process. To this effect, slagging and deposition on the boiler heating surface is a multidisciplinary practical problem that involves the boiler, fuel chemistry, multiphase fluid dynamics, heat and mass transfer, combustion theory, and technology and material science principles. This chapter only introduces content related to heat transfer in furnaces. Interested readers are urged to refer to the literature.

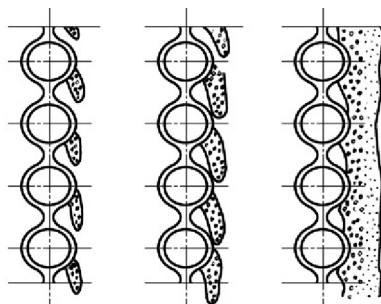


FIGURE 6.1 Slagging on a water wall.

### 6.1.2 Formation and Characteristics of Deposition and Slagging

Let's first define some different types of deposition and slagging, first by examining the morphology of deposition and slagging on a boiler's heating furnace. During boiler operation, slagging happens only when a portion of the ash particles are viscous enough to adhere to the wall's surface. An ash layer first forms on the surface, then it extends from the heating surface to the furnace interior until reaching the fusion state. Fig. 6.1 shows the process of slagging on a furnace heating surface.

The slagging process is closely related to the flow and temperature field inside the furnace. When part of the gas in the furnace stagnates or changes flow direction, ash particles entrained by the gas may deposit on the furnace wall due to inertia settlement. If the furnace wall temperature is high enough, or the ash surface is molten, ash accumulates to a certain degree on the furnace wall then flows downward to cooler places such as manholes, sight holes, or any measuring holes due to gravity, then condenses into a slag lump looking like a stalactite as shown in Fig. 6.2.

The typical deposition and slagging morphology of convective heating surface tube bundles is shown in Fig. 6.3. Deposition is most likely on the leeward side of the tubes; when gas flows across the tube bundles, a stagnant area forms on this leeward side. Ash particles deposit, again, due to inertia, forming slag arches and bridges. When the temperature is low, the deposited ash is present in the form of fine particle powder.

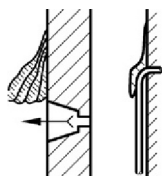
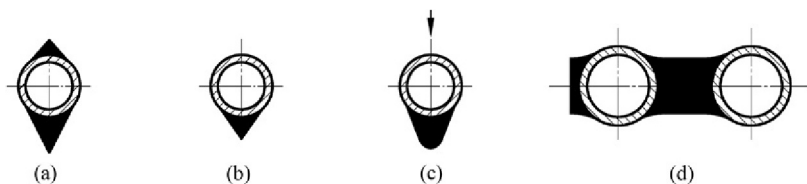


FIGURE 6.2 Sight hole and slag lumps on a leading tube.



**FIGURE 6.3 Deposition morphology.** (a) Bilateral wedge deposition. (b) Unilateral wedge deposition. (c) Unilateral melt transformative deposition. (d) Deposition bridge.

The processes of deposition and slagging are complicated, and are affected by alternating physical and chemical factors. As such, there are various types of deposition and slagging that are sometimes difficult to distinguish, but can be roughly classified according to certain properties.

According to ash particle temperature, deposition and slagging can be classified as fusion slag, high-temperature deposition, or low-temperature deposition. When the gas temperature is higher than  $800^{\circ}\text{C}$ , the ash particle temperature reaches the fusion point and the slag is fusion slag. When the gas temperature is  $600\sim 800^{\circ}\text{C}$ , the ash particles are solid and a high-temperature deposition is formed. When the gas temperature is lower than  $600^{\circ}\text{C}$ , fine ash particles on the heating surface of the tubes form a low-temperature deposition.

Deposition can be divided by strength into loose deposition and viscous deposition. Loose deposition is primarily unilateral wedge deposition formed on the leeward of the tubes. Viscous deposition forms on the windward of the tubes when velocity is very low and ash particles are very small, and grows toward the gas flow. Unlike loose deposition, viscous deposition will not stop growing upon reaching a certain size, but instead will continue to grow. As a result, the bundle flow resistance increases until the gas passage is completely blocked.

The properties and differences of loose deposition and viscous deposition are shown in [Table 6.1](#).

Let's look at some specific processes next, starting with the heating surface deposition process. SEM (scanning electron microscope) analysis of heating surface deposition has shown that deposition formation can be divided into three stages.

1. Initial depositions form the substrate. One type of deposition, iron-rich fusion slag, hits and sticks to the tube wall in a tight, iron-rich, spherical glass ball; the other type of deposition is mainly formed by the sublimation and agglomeration of sintering, or the high-temperature effects of aluminum-rich andalusite with silica and aluminum minerals.
2. Fly ash particles then adhere to the top of the substrate. The strength of the deposition layer is increased due to mutual particle adherence. A layer of viscous clusters is formed as the deposition grows. The thermal insulation of the deposition layer raises the temperature of the deposition layer, causing stronger particle adhesion.

**TABLE 6.1** Differences Between Loose and Viscous Deposition

Factors considered	Loose deposition	Viscous deposition
Forming location when flowing across bundles	Mainly on leeward side, casually on windward side	Mainly formed on windward side
Growing characteristics	Growth until force balance of fine ash deposition and deposited layer collapse caused by large particles	Infinite growth tendency
Flow resistance	Does not increase bundle resistance	Increases bundle resistance obviously
Ash content in fuel	No influence basically	Deposition becomes severe with large amount of ash
Gas velocity	Increasing velocity decreases deposition size	Increasing velocity increases deposition
Mechanical strength	Loose without mechanical strength	With various mechanical strength

3. As furnace temperature increases, the depositing rate also increases, even causing deposition sintering, so that forms the slag layer.

Now, let's take a look at the slagging process on a heating surface. For pulverized furnaces, the fusible matter in the ash first melts to liquid during combustion, then shrinks into a spherical shape under the effects of surface tension. The fused spherical ash particles have high density, and readily separate from the gas into the ash hopper or slag pool, or adhere to the furnace heating surface. The nonmelted ash particles maintain their original irregular shape. Low-density porous particles form when the combustible matter burns out, then escape the furnace to form fly ash or build up on the cooler heating surface.

In the high-temperature zone in a furnace, the ash in the coal is in a fused or quasi-fused state. If the ash is not cold enough to become solid before reaching the heating surface, the ash still has strong adhesive capacity and will readily adhere to the heating surface or furnace wall facing the high-temperature gas or flame. Fusible or easily gasified substances (such as alkali metal compounds) volatilize rapidly and enter into the flue gas. When the temperature decreases, these substances condense partially on the heating surface to form an initial ash layer. As the adhesive force of the ash layer increases, the thickness of the ash layer increases, and the surface temperature of the ash layer increases. If the fuel ash fusion point is low, the ash forms a plastic slag film with high viscosity when it reaches the ash deformation temperature, then sinters gradually.

Research has shown that the process involves three stages.

1. Diffusion: where a thin ash deposition layer is formed around the tubes that is not affected by flue gas velocity.
2. Internal sintering: where the ash layer is formed on the windward of the tubes because of the hitting of ash particles (about several millimeters in thickness). Particles in this layer bond with each other due to surface viscosity, then gradually sinter into solid form.
3. External sintering: where as the internal sintering layer grows, the ash surface temperature increases, even up to the gas temperature. When the gas temperature and alkali metal proportion in the ash are high enough, a fusion layer is formed on the windward of the ash layer. These fusion materials can further capture oncoming particles and bond with them to form high-strength ash deposition.

Naturally, if the flow field in a furnace causes fuel jet stream deflection, a high-temperature flame blows directly onto the heating surface and directly causes slagging without the above stages.

### 6.1.3 Damage of Deposition and Slagging

According to the aforementioned analysis of the mechanisms and processes of deposition and slagging in the boiler, the following problems deserve attention:

1. Deposition and slagging reduce the heat transfer ability of the furnace's heating surface; after ash particles deposit on the heating surface, the thermal conductivity is small and the thermal resistance becomes greater. The heat transfer ability decreases by 30~60% after being covered by ash, causing upward movement of the flame center in the furnace, decreased absorption of heat, and increased furnace outlet temperature.
2. Due to increased furnace outlet temperature, fly ash readily adheres to the pendant superheater and convective superheater of the back-end high-temperature zone, which causes deposition, slagging, and corrosion in the superheater. This not only influences heat transfer, but also can lead to corrosion and bursting of the tubes.
3. Severe deposition will cause blockage in the economizer and air preheater gas passage, deteriorating the heat transfer and increasing the exhaust gas temperature, which decrease boiler thermal efficiency and operational economy.
4. Increased total thermal resistance (namely, decreased effective heating area) leaves the boiler unable to keep working at rated load in relation to the designed coal consumption, thus, coal feed has to be increased, causing increased furnace outlet temperature, in turn making ash more readily adhere to the heating surface, and forming a vicious circle. Dangerous accidents such as superheater and economizer blockage, cracks, air preheater blockage, and/or air leaking, then result. Increased furnace outlet temperature

may raise the superheated steam temperature, causing the superheater tubes to work above allowable temperatures.

5. Under the effects of high-temperature gas, ash on the water wall or high-temperature superheater will react with the metal on the tube wall to form high-temperature corrosion. Research has shown that the average water wall corrosion rate is 0.8~2.6 mm/a with high-temperature corrosion, therefore, deposition and slagging are the beginning of high-temperature corrosion.

The above problems caused by deposition and slagging directly result in economic losses including decreased average boiler thermal efficiency, decreased boiler output, decreased available operation time, and increased maintenance time and cost. Avoiding deposition and slagging should be given a great deal of attention during the design, operation, and maintenance of the boiler. It is also important to note that designers should avoid calculating blindly according to ideal, purely theoretical situations, or the results will not reflect actual situations in practice.

### 6.1.4 Ash Composition

For convenience, we'll use a coal and a pulverized coal-fired boiler as examples to illustrate the influence of fuel composition and ash properties on heating surface deposition and slagging. The ash composition is very complex, and includes mainly Si, Al, Fe, Ti, Ca, Mg, V, Mn, K, Na, S, P, and O. During chemical analysis, these elements are usually denoted by oxide forms (such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  or  $\text{FeO}$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{V}_2\text{O}_5$ ,  $\text{Mn}_3\text{O}_4$  or  $\text{MnO}$ ,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ ,  $\text{SO}_3$ , and  $\text{P}_2\text{O}_5$ .) In addition to the oxides, these elements are present in the form of silicates, aluminosilicates, and sulfates. The oxide concentration in ash from high to low is  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$ .

The ash composition combines with the following factors to influence the deposition and slagging.

1. Thermodynamic conditions: gas velocity, gas flow direction, gas temperature, and wall temperature.
2. Operation conditions: coal particle size, fly ash concentration, excess air coefficient, boiler local heat flux, and boiler output.
3. Geometric conditions: tube diameter, tube bundle pitch, number of tube rows, and the approach taken for enhancing heat transfer such as spiral pipes or a bundle with fins.

## 6.2 EFFECTS OF ASH DEPOSITION AND SLAGGING ON HEAT TRANSFER IN FURNACES

Let's start this section with a look into changes in the thermal efficiency coefficient  $\eta$  during deposition and slagging processes. According to the information provided earlier, the furnace wall can be considered a graybody, and the



relationship among its own radiation, reflected radiation, projected radiation, and radiosity can be expressed as follows:

$$q_R = \varepsilon \sigma T^4 + (1 - \varepsilon) q_I \quad (6.1)$$

The radiative heat transfer flux  $q$  is the amount of heat transferred between this surface and the external system. For energy balance, calculate the following:

$$q = q_I - q_R \quad (\text{It is positive if heat is received.}) \quad (6.2a)$$

or

$$q = \varepsilon q_I - \varepsilon \sigma T^4 \quad (6.2b)$$

The effect of fuel characteristics, combustion mode, and boiler thermal load on the in-furnace heat transfer can be lump-sum represented by the thermal efficiency coefficient  $\psi$ , which can be measured from experiments. Projected radiation and radiosity can be measured with a radiation heat flowmeter. If the heat flowmeter faces the flame, the projected radiation  $q_I$  from flame to wall can be measured; if the heat flowmeter faces the water wall, the radiosity  $q_R$  from wall to flame can be obtained. The thermal efficiency coefficient of the water wall is:

$$\psi = \frac{q_I - q_R}{q_I} = \frac{q}{q_I} \quad (6.3)$$

where  $\psi$  denotes the ratio of heat absorbed by the water wall to the projected radiation. The larger  $\psi$  is, the stronger the radiative heat transfer between the water wall and flame.

The factors influencing the water wall thermal efficiency coefficient  $\psi$  include the following.

1. The emissivity of the water wall surface, namely, the ash surface emissivity after deposition and slagging, is related to the slagging structure and temperature. The surface emissivity of loose slag is lower than that of tight slag. The emissivity of the water wall is usually around 0.8.
2.  $\psi$  is proportional to the difference of projected radiation and radiosity. If projected radiation is large but reflected radiation is also large, then the thermal efficiency coefficient will not necessarily increase. Fig. 6.4 shows where the measured thermal efficiency coefficient varies along the furnace height of a 230 t/h wet bottom boiler. Projected radiation is high at the slag melting zone, but the radiosity is also high, so  $\psi$  is low. At the upper stage of the furnace, projected radiation is low because the gas temperature is low, but radiosity is also low, so the thermal efficiency coefficient  $\psi$  is high.
3.  $\psi$  is related to the temperature of the water wall, namely the temperature of the ash surface. Surface temperature is related to the thickness of deposition and slagging. If the ash layer is thin, the thermal conduction resistance of

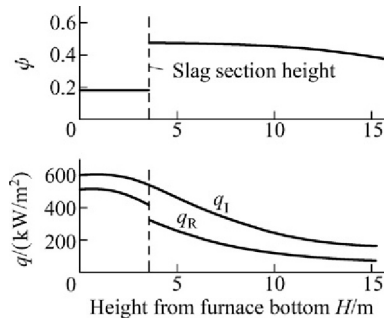


FIGURE 6.4 Changes in thermal efficiency coefficient and heat flux of a 230 t/h wet bottom furnace.

ash is low, and the slag surface temperature is low. If the ash layer is thick, the thermal conduction resistance increases and the slag surface temperature grows rapidly. A previous study provided the example depicted in Fig. 6.5 [15]. For the case of the same flame temperature, when slag layer thickness is 5 mm, the difference between slag surface temperature and flame temperature is about  $350^\circ\text{C}$ , whereas at slag layer thickness of 50 mm, the slag surface temperature is only about  $40^\circ\text{C}$  lower than flame temperature. Meanwhile, the radiative heat transfer of the flame and water wall decreases from  $200 \times 10^3 \text{ W/m}^2$  to  $30 \times 10^3 \text{ W/m}^2$ . In brief, the influence of surface temperature (slag layer temperature) is the vital one.

Finally, based on Eq. (6.3) and the conception of radiative heat transfer:

$$\psi = \frac{q_I - q_R}{q_I} = \frac{q_I - [\varepsilon \sigma T^4 + (1 - \varepsilon) q_I]}{q_I} = \varepsilon \left( 1 - \frac{\sigma T^4}{q_I} \right) \quad (6.4)$$

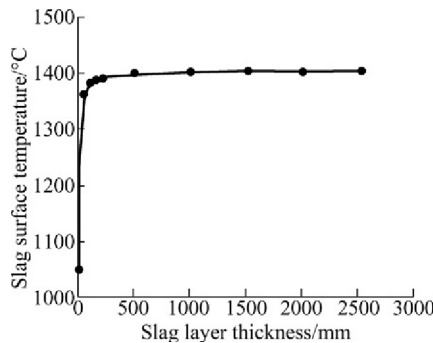


FIGURE 6.5 The relationship between slag layer thickness and slag layer surface temperature.

Evidenced by this equation, the thermal efficiency coefficient  $\psi$  is related to water wall surface emissivity  $\varepsilon$ , surface temperature  $T$ , and projected radiative heat flow to water wall surface  $q_I$ , where  $q_R$  is the effective radiative heat flow of the water wall surface.

In the absence of deposition, the water wall surface temperature equals the metal tube surface temperature, which is close to the temperature of the working medium in the tube without considering the thermal resistance of scales deposited on the inner side of the heating tubes. With the same projected radiative heat flow  $q_I$ ,  $\frac{\sigma T^4}{q_I}$  is smallest at this time while the thermal efficiency coefficient  $\psi$  reaches its maximum. After deposition, the water wall surface temperature  $T$  is equivalent to the ash surface temperature and varies with ash layer thickness/compactness (the thicker the ash layer, the higher the ash layer surface temperature). When the ash is thick enough that the ash layer surface temperature rises close to the flame temperature, the difference is nearly zero, and the heat transfer tends toward zero. At this time, the thermal efficiency coefficient  $\psi$  reaches its minimum (also zero).

Let's consider the influence of the fouling factor  $\zeta$  on heat transfer. According to the above definition, the fouling factor  $\zeta$  is:

$$\zeta = \psi/x \quad (6.5)$$

where  $x$  is the effective configuration factor of the water wall tube, and is dependent on the structure of the water wall. Large coal boilers usually adopt a membrane wall with fins ( $x = 1$ ), thus the fouling factor is equal to the thermal efficiency coefficient. During boiler design and analysis, the fouling factor is usually used instead of the thermal efficiency coefficient. The fouling factor of a general boiler is detailed in Table 3.1.

For a water wall with refractory material, its fouling factor is determined by the following equation:

$$\zeta = 0.53 - 0.25 \frac{T_{FT}}{1000} \quad (6.6)$$

where  $T_{FT}$  is the fluid temperature of ash.

When fouling factor  $\zeta$  decreases, the ability of radiative heat transfer weakens and the heat absorbed by the furnace decreases, causing a rise in the furnace outlet gas temperature.

### 6.2.1 Heat Transfer Characteristics and Ash Layer Calculation with Slagging

The ash deposition coefficient  $\rho$  is characterized by the thermal conduction resistance of the ash layer on the water wall, which is related to fuel type and water wall mode. Table 6.2 shows the recommended values of ash deposition coefficients for the water wall. The ash deposition coefficients for other types

**TABLE 6.2** Recommended Ash Deposition Coefficient Values

Water wall type	Fuel/combustion type	$\rho/(\text{m}^2\cdot^\circ\text{C}/\text{W})$
Bare water wall	Gas	0
	Heavy oil	0.0017
	Pulverized coal	0.0034
	Coal powder $R_{90} = 12\text{--}15\%$	0.0052
	Oil shale	0.0060
	Grate-firing furnace	0.0026
With refractory coating		0.0067
Water wall with refractory brick		0.0086

of heating surface can be found in D6.31, D6.33, D6.37, and D6.38 of the Appendix.

Thermal conduction resistance is related to ash structure and thickness. The following balance equation describes the relationship between heat transfer flow and slag layer thickness (or ash deposition coefficient):

Measuring the heat transfer process provides the sum of radiative heat transfer and convective heat transfer absorbed by the heating surface, which is equal to the amount of heat both conducted through the ash layer and the convective heat transferred into the working medium in the water wall tubes, and can be expressed as follows:

$$\sigma a_F (T_g^4 - T_s^4) + h_2 (T_g - T_w) = \frac{T_s - T_t}{\rho} \quad (6.7)$$

$$\frac{T_s - T_t}{\rho} = h_1 (T_t - T_1) \quad (6.8)$$

where  $T_g$  is the flame temperature in the furnace,  $T_s$  is the ash layer surface temperature,  $T_t$  is the average temperature of the water wall tube (ignore any temperature difference caused by thermal resistance of the tube itself and internal deposition), and  $a_F$  is furnace emissivity, which is calculated by flame emissivity  $\varepsilon_g$  and slag surface emissivity  $\varepsilon_s$  (see the following):

$$a_F = \frac{1}{\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_s} - 1} \quad (6.9)$$

$h_2$  is the convective heat transfer coefficient from the flame to the ash surface,  $h_1$  is the heat transfer coefficient between the water wall tube inner surface and the working medium in the tube,  $T_1$  is the working medium temperature,  $\sigma$  is the radiation constant, and  $\rho$  is the ash deposition coefficient (ash thermal conduction

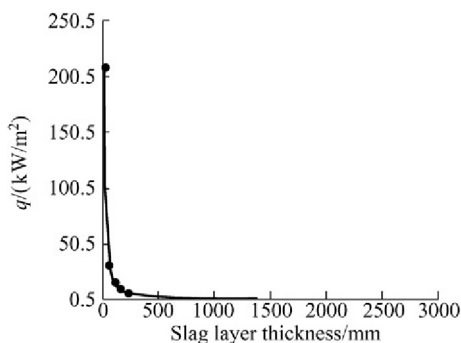


FIGURE 6.6 The relationship between slag layer thickness and heat flux.

resistance  $\delta/\lambda$ , where  $\delta$  is the ash layer thickness and  $\lambda$  is the ash thermal conductivity). From Eqs. (6.7) and (6.8), the relationship between heat flux  $q$  and ash thickness can be calculated (supposing  $\lambda$  is constant), as shown in Fig. 6.6.

The following is a practical example.

#### Example 6.1

A pulverized coal boiler has capacity 130 t/h, furnace water wall area  $A = 479.5 \text{ m}^2$ , calculated fuel consumption  $B_{\text{cal}} = 4.437 \text{ kg/s}$ , and amount of heat transfer in furnace for 1 kg fuel burnt  $Q_r = 12246 \text{ kJ/kg}$ . Known deposition thickness is 0.5 mm and deposition thermal conductivity is  $0.1 \text{ W/(m}^\circ\text{C)}$ . Calculate the temperature inside and outside the deposition layer.

The total heat absorbed by the water wall is:

$$Q_r B_{\text{cal}} = 12246 \times 4.437 = 54335.5 \text{ kW}$$

The heat flux of the heating surface area is:

$$q = \frac{Q_r B_{\text{cal}}}{A} = 113.3 \text{ (kW/m}^2\text{)}$$

The temperature difference is:

$$\Delta t = \frac{\delta}{\lambda} q = \frac{0.5 \times 10^{-3}}{0.1} \times 113.3 = 566.5^\circ\text{C}$$

If the water wall surface temperature is  $450^\circ\text{C}$ , then the external ash temperature is  $1016.5^\circ\text{C}$ .

### 6.2.2 Heat Transfer Calculation with Deposition and Slagging

Furnace heat transfer calculation equations are obtained based on radiative heat transfer. After comprehensive boiler tests, the integrated influence of boiler

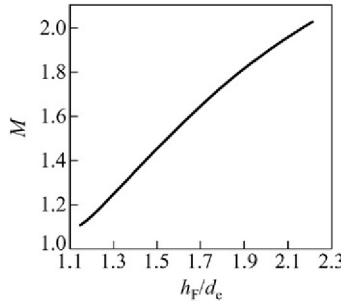


FIGURE 6.7 Furnace geometric shape coefficient.

structure, combustion mode, fuel characteristics, and deposition and slagging can be reflected by equations using coefficients  $M$  and  $\psi$ .

The furnace outlet gas temperature  $T_F''$  can be determined using Eq. (5.27):

$$T_F'' = \frac{T_a}{M \left( \frac{\sigma \psi A \tilde{a}_F T_a^3}{\phi B_{\text{cal}} V C} \right) + 1}$$

When furnace structure, fuel characteristics, and boiler parameters are given, the furnace outlet gas temperature can be calculated from the above equation. The influence of deposition and slagging on the furnace thermal efficiency coefficient  $\psi$  has been introduced before in this section.

Coefficient  $M$  is related to furnace geometric shape, and is a function of the ratio of furnace height  $h_F$  to furnace cross section equivalent diameter  $d_e$ . As a previous study pointed out, according to a large number of tests on a dry bottom pulverized coal boiler, the relationship of  $M$  and  $h_F/d_e$  can be obtained as shown in Fig. 6.7 [15]. The furnace cross section equivalent diameter can be calculated using the following equation:

$$d_e = \frac{4F}{U} \quad (6.10)$$

where  $F$  is the furnace cross section area, and  $U$  is the perimeter of the furnace cross section.

## 6.3 EFFECTS OF ASH DEPOSITION AND SLAGGING ON HEAT TRANSFER IN CONVECTIVE HEATING SURFACES

### 6.3.1 Effects of Severe Ash Deposition and Slagging

Radiative heat transfer in a furnace worsens owing to ash deposition and slagging, leading to increases in the furnace outlet gas temperature, and increases in the heat load of the convective heating surface positioned immediately after

the furnace exit. Previous research has provided a good example of this [15]. Calculation of a 600 MWe boiler water wall showed that as deposition grew severe, the fouling factor  $\zeta$  decreased from 0.45 to 0.25 and the furnace outlet gas temperature increased by 65°C. The more serious the deposition was, the higher the furnace outlet gas temperature. As furnace gas flows through the platen superheater, reheater, superheater, economizer, and air preheater, the inlet gas temperature of all heating surfaces increases. The closer the heating surface is located downstream from the furnace exit, the higher the magnitude of the temperature rise. The platen superheater inlet gas temperature increases by 145°C, the last-stage reheater inlet gas temperature increases by 80°C, the economizer inlet gas temperature increases by 12°C, and the air preheater inlet gas temperature increases by 5°C when deposition is severe. To reiterate, deposition and slagging in the furnace have a considerable impact on the high-temperature heating surface, and to this effect, the security issue attributable to overheating of the tube wall of the reheater and superheater needs special attention.

### 6.3.2 Basic Heat Transfer Equation for Convective Heating Surfaces

For heating surfaces in the boiler back-end ductwork, the working medium absorbs heat from the gas by convective heat transfer. These heating surfaces are therefore called “convective heating surfaces.” Convective heating surfaces in large boilers include slag screens, convective superheaters, reheaters, economizers, and air preheaters, all of which belong to recuperative heat exchangers, follow the same heat transfer principle, and are calculated in almost the same way.

The thermal balance equation of the convective heating surface gas side is:

$$Q = \varphi (I' - I'' + \Delta\alpha I_{\text{air}}^0) \quad (6.11)$$

The thermal balance equation of the working medium side is:

$$Q = \frac{D(i'' - i')}{B_{\text{cal}}} \quad (6.12)$$

The heat transfer equation is as follows:

$$Q = \frac{K\Delta tA}{B_{\text{cal}}} \quad (6.13)$$

where  $Q$  is the convective heat transfer of the heating surface,  $I'$  is the gas enthalpy at the heating surface inlet,  $I''$  is the gas enthalpy at the heating surface outlet,  $\Delta\alpha$  is the air leakage coefficient within the calculated heating surface,  $I_{\text{air}}^0$  is the theoretical leaked air enthalpy (usually the enthalpy of cold air),  $D$  is the flow rate of the working medium,  $i'$ ,  $i''$  is the working medium enthalpy at the heating surface inlet and outlet, respectively,  $B_{\text{cal}}$  is the designed fuel supply rate (really burnt),  $A$  is the convective heating surface area (usually the external area of the heating surface tube whereas the mean diameter between the inner

and external diameters should be used for a tubular air preheater area calculation),  $\Delta t$  is the average temperature difference between the gas and the working medium, and  $K$  is the convective heat transfer coefficient.

The effects of deposition and slagging on heat transfer are integrated by convective heat transfer  $K$  in the following heat transfer equation:

$$K = \frac{1}{\frac{1}{h_1} + \frac{\delta_a}{\lambda_a} + \frac{\delta_w}{\lambda_w} + \frac{\delta'}{\lambda'} + \frac{1}{h_2}}$$

(The meaning of this equation was discussed in detail in Section 5.5.)

The metal walls of tubes in the boiler are very thin and their thermal conductivity is large. Therefore, thermal resistance  $\delta_w/\lambda_w$  is small enough to be ignored. Because scale deposition under normal operating conditions does not occur, the resistance of scale deposition  $\delta'/\lambda'$  is not considered. Bear in mind that if there is deposition, its thermal conductivity is very small, so the heat transfer coefficient will drop sharply.

The thermal resistance of the ash layer is related to many factors including fuel type, gas velocity, tube diameter and arrangement, ash particle size, and others. At present, the ash deposition coefficient  $\rho = \delta_a/\lambda_a$  or the effectiveness factor  $\psi$  is adopted to account for this. To distinguish this factor from the furnace thermal efficiency coefficient,  $\psi_a$  is used here.  $\psi_a$  is defined as the ratio of the heat transfer coefficient of a dirty (fouled) tube  $K$  and the heat transfer coefficient of a clean tube  $K_0$ :

$$\psi_a = K/K_0 \quad (6.14)$$

The heat transfer coefficient can be expressed by the following equation:

$$K = \frac{1}{\frac{1}{h_1} + \rho + \frac{1}{h_2}} \quad (6.15a)$$

or by:

$$K = \psi_a \frac{1}{\frac{1}{h_1} + \frac{1}{h_2}} \quad (6.15b)$$

The heat transfer coefficient from the gas to the tube wall can be calculated by the following equation:

$$h_1 = \xi(h_c + h_r) \quad (6.16)$$

where  $\xi$  is a utilization coefficient that makes a correction for reduced absorption of heat due to nonuniform flow of gas passing across the heating surface. Note that for the evaporating heating surface and economizer, the heat transfer



coefficient from the tube wall to the working medium  $h_2 \gg h_1$ , thus thermal resistance  $1/h_2$  can be ignored.

Based on experimental data for cross-flow staggered tube bundles in solid fuel fired boilers, the effect of deposition on the heat transfer coefficient can be observed according to the ash deposition coefficient. For a superheater:

$$K = \frac{1}{\frac{1}{h_1} + \rho + \frac{1}{h_2}} \quad (6.17)$$

For an economizer and boiler convection bank:

$$K = \frac{1}{\frac{1}{h_1} + \rho} \quad (6.18)$$

The ash deposition coefficient is determined by experimental data, as discussed in [Section 6.3.3](#).

For cross-flow in-line bundles in solid fuel fired boilers, heat transfer coefficients are calculated according to the effectiveness coefficient. For a superheater:

$$K = \psi_a \frac{1}{\frac{1}{h_1} + \frac{1}{h_2}} \quad (6.19)$$

For an economizer and boiler convection bank:

$$K = \psi_a h_1 \quad (6.20)$$

where for anthracite and mean coal,  $\psi_a = 0.6$ ; for bituminous coal and lignite,  $\psi_a = 0.65$ ; for oil shale,  $\psi_a = 0.5$ .

For tubular air preheaters, the influence of ash deposition and the uneven gas flow field is considered using the utilization coefficient  $\xi$  as follows:

$$K = \xi \frac{1}{\frac{1}{h_1} + \frac{1}{h_2}} \quad (6.21)$$

### 6.3.3 Coefficients Evaluating the Ash Deposition Effect

“Convective heating surface deposition” refers to the deposition process on convective heating surfaces by gas laden with ash. Heating surface deposition severely influences heat transfer; heat transfer capacity generally decreases by about 30%, and potentially even up to 50%, after deposition. Fouling effects are observed using the ash deposition coefficient  $\rho$ , the effectiveness coefficient  $\psi_a$ ,

and the utilization coefficient  $\xi$  during a convective heat transfer calculation. Because the deposition process is related to fuel type, heating surface arrangement, and operating conditions, the above coefficients can only be obtained from model experiments and measurements taken during practical operation. We'll discuss them separately below.

### 1. Ash deposition coefficient $\rho$

The ash deposition coefficient is the thermal resistance caused by deposition on the convective heating surface,  $\frac{\delta_a}{\lambda_a}$ . Because deposition layer thickness  $\delta_a$  and thermal conductivity  $\lambda_a$  are difficult to measure, the recommended  $\rho$  is determined based on the difference of the reciprocal of the dirty tube wall heat transfer coefficient  $K$  and the clean tube wall heat transfer coefficient  $K_0$ :  $\rho = \frac{1}{K} - \frac{1}{K_0}$ .

For loose deposition, field tests have shown that  $\rho$  is related to gas velocity, heating surface arrangement, fuel characteristics, and ash particle size. The higher the gas velocity is, the smaller the  $\rho$  value. Gas easily washes the back side of a tube if the tubes are in a staggered arrangement, so there is less deposition on the leeward of the tubes and the value of  $\rho$  is small. If the arrangement of the tubes is dense (the vertical spacing is small), the gas more readily washes the front of the tubes, which decreases the  $\rho$  value. If large-diameter tubes are in an in-line arrangement, deposition tends to be severe and the  $\rho$  value tends to be high. As for the ash particle size, the bigger the particle is, the greater the self-cleaning effect is, and as a result, the ash deposition becomes slow and the  $\rho$  value decreases.

For staggered bundles arrangements including a single row of tubes when burning solid fuel,  $\rho$  can be calculated using the following equation:

$$\rho = C_d C_a \rho_0 + \Delta\rho \quad (6.22)$$

where  $\rho_0$  is the basic ash deposition coefficient related to gas velocity  $w_g$ , which is obtained as shown in Fig. 6.8.  $S_2$  is the vertical pitch of tube rows,  $d$  is the tube external diameter, and  $C_d$  is the correction coefficient for tube diameter (Fig. 6.8).  $C_a$  is the correction coefficient for ash particle size,  $C_a = 1 - 1.18 \lg \frac{R_{30}}{33.7}$ , and  $R_{30}$  is the mass percentage of ash particles larger than 30  $\mu\text{m}$ . Generally, for coal and oil shale,  $C_a = 1.0$ ; for peat,  $C_a = 0.7$ .  $\Delta\rho$  is an additional correction value (See Table D19).

For a platen heating surface, the ash deposition coefficient is related to fuel characteristics, average gas temperature  $\bar{T}_g$ , and soot blowing condition, which can be determined as shown in Fig. D9 of the Appendix.

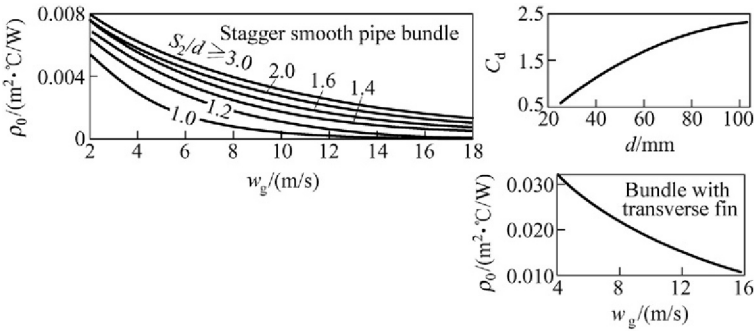


FIGURE 6.8 Basic ash deposition coefficient and correction coefficient.

## 2. Effectiveness factor $\psi_a$

Eq. (6.14) indicates that the effectiveness factor  $\psi_a$  reflects the heat transfer coefficient of a dirty tube wall and a clean tube wall. The effectiveness factor is adopted regardless of fuel type for the slag screen of a large boiler or tube bank of a small boiler, and also for the convective heating surface of a boiler burning liquid or gas fuel.

The effectiveness factor  $\psi_a$ , as well as the ash deposition coefficient  $\rho$ , depend on fuel characteristics, gas velocity, heating surface structure, and working systems. The value of  $\psi_a$  should be determined according to several different conditions. For heating surfaces such as convective in-line superheaters, slag screens, boiler banks, reheaters, and the transition areas of once-through boilers burning lean coal and anthracite,  $\psi_a = 0.6$ ; burning bituminous coal, lignite, and middling,  $\psi_a = 0.65$ ; burning oil shale,  $\psi_a = 0.5$ . For heavy oil fired boilers,  $\psi_a = 0.5 \sim 0.7$  for all the convective heating surfaces except for the air preheater, which is dependent on the gas velocity and soot blowing condition.

For gas fuel fired boiler the effectiveness factor is taken to consider the influence of fouling on heat transfer in all types of convective heating surface. For single-stage economizers with inlet gas temperatures below  $400^\circ\text{C}$ , first stage economizers with a two-stage arrangement, and reheaters,  $\psi_a = 0.85$ .

## 3. Utilization coefficient $\xi$

The utilization coefficient  $\xi$  is a correction that reflects any uneven flow onto the heating surface and the resultant reduction in utilization efficiency of the heating surface. During calculation of the convective heating surface, the  $\xi$  value is generally considered. For convective heating surfaces with mixed flow,  $\xi$  is 0.95. For cross flow heating surfaces of modern boilers, due to their simple structure and effective sweeping,  $\xi$  is 1. For boiler evaporating banks with complex gas flow,  $\xi$  is 0.9.

To calculate the gas side heat transfer coefficient of a platen superheater,  $\xi$  should be adopted to consider the influence of uneven flow from the gas to the

platen surface, because gas velocity in the equation of the heat transfer coefficient must be determined by the average flow velocity assuming gas flowing uniformly across the heating surface. Because most platen heating surfaces are arranged at the position where flue gas in the furnace top enters the horizontal flue gas passage, gas velocity in the furnace exit section is uneven (despite the arrangement of the furnace nose or the fact that the combustor is arranged according to the furnace air dynamic field). The convective heat transfer coefficient has to be corrected, to this effect, and the utilization coefficient should be measured from experiments. When average gas velocity  $\omega_g \geq 4$  m/s,  $\xi = 0.85$ ; as gas velocity decreases, the influence of uneven flow increases and the  $\xi$  value decreases.

For tubular air preheaters, the utilization coefficient  $\xi$  is the influence of the air side where the air cannot flow across bundles uniformly due to direction turning of air flow induced by the baffling plate. The correction method of this influence involves multiplying the heat transfer coefficient under average velocity by a factor less than 1, which is similar to the correction method for the gas side of a dirty tube. During heat transfer calculation the combined effect of the air side and flue gas side is considered and denoted by utilization coefficients.

Under all the conditions introduced above, the values of  $\rho$ ,  $\psi_a$ , and  $\xi$  are suitable for the situation of a single-fuel boiler. If the boiler uses blended fuel, such as coal–oil blends or oil–gas blends, the values of these coefficients should be calculated according to the degree of fouling. If boilers burn gas fuel after solid fuel, they should be calculated in accordance with the solid fuel burned.

The ash deposition coefficient  $\rho$ , effectiveness factor  $\psi_a$ , and utilization coefficient  $\xi$  are empirical corrections for the additional thermal resistance caused by ash deposition on the heating surface, which is obtained from experiments. Generally, for solid fuel and cross flow staggered bundles, the ash deposition coefficient  $\rho$  is applied to correct the influence of heating surface fouling on heat transfer. For in-line arranged bundles and various fuels, ash deposition is usually accounted for by the effectiveness factor  $\psi_a$ . For air preheaters, besides the thermal resistance of ash deposition, the effects of an uneven flow field are quite significant, so the utilization coefficient  $\xi$  is adopted to reflect both.