changers with Sinusoidal Time Dependent Internal Heat Generation, Thesis, University of Michigan (1960).

W. J. Yang, et al., *Trans. ASME*, Series C, Vol. 83, No. 3 (1961), p. 321.

J. W. Rizika, *Trans. ASME*, Vol. 76, No. 3 (1954), p. 411.

(3) For example, the 20%-72%-20% Z-type heat exchanger is designed for the porosities of 0.81 for the gas side and 0.71 for the air side. For the evaluation of the temperature distribution, α is affected by the porosity.

(4) Concerning those statements given in the Introduction, the author likes to quote a sentence by

Append-Table 1

	Heat exchanger I		II		III
	cross flow	counter flow	cross flow	counter flow	
α_h	45.2	45.2	44.3	44.3	40.7
α_c	45.2	45.2	110	83.2	68.6

Prof. Awano in Chapter 5, Reference

(4) (in Japanese): "Heat exchangers are not often used for a jet plane whose main aim is to increase its thrust in order to gain a higher speed".

621.181.7:662.932

Thermal Design of a Slag Tap Boiler Furnace*

By Tatsuo EGUSA**

In the conventional design of slag-tap boiler furnaces, certain complicated procedures based on experience have been required because of their variety of construction. A new comprehensive design is explained here, being deduced from the thermal theory, so that a simplified design method may be introduced from the relation between the furnace heat-release and the form factor, and determined by the statistical data. Further, from the latest experimental information, a general viscosity equation of molten coal-ash slag is derived and the thickness of a fluid slag film is determined by the author.

In particular, a simplified equation for calculation is deduced from the inherent operation conditions of the slag tap boilers.

1. Introduction

For the design of a dry bottom boiler furnace, the procedure includes the determination of the furnace heat release by the previous experience, the calculation of the furnace volume and the sectional area, and then the height of the furnace is obtained by the sectional heat release of the furnace.

After the principal dimensions of the boiler furnace are decided, the furnace wall area is calculated, and then the heating surfaces of water cooling walls are determined. On the other hand, for the slag tap boiler, the furnace construction itself is not so simple as that of the dry bottom, thus the slag tap furnace, including the cyclone furnace, is designed by a complicated procedure; its principal dimensions and the heating surfaces of the furnace are projected by repeated trial method of calculation,

which requires both technical data and practical experience.

However the author proposes here a design method for slag tap boiler furnaces by using the furnace form factor, prepared by Grasme's data⁽¹⁾ and referring to the Zinzen's thermal calculation method⁽²⁾, and thereby establishing the comprehensive, practical and theoretical, procedure of slag tap boiler furnace design, by which trial calculation and design can be omitted.

2. Thermal calculation equation

The radiation heat absorption by the walls of the pulverised coal firing boiler furnace is calculated by the following equation, assuming its flame to have a spherical and solid surface

$$Q = \frac{C_s F_F}{\frac{1}{\epsilon_F} + \frac{F_F}{F_W} \left(\frac{1}{\epsilon_W} - 1 \right)} \left[\left(\frac{T_F}{100} \right)^4 - \left(\frac{T_W}{100} \right)^4 \right] \quad \dots\dots\dots (1)$$

where, T_F and T_W ; Temperature of flame surface

* Received 6th December, 1960.

** Chief of Atomic Section, Engineering Department, Yokoyama Engineering Co., Chyuo-ku, Tokyo.

and furnace wall ($^{\circ}\text{K}$), ε_F and ε_W ; surface emissivity of flame and furnace wall, C_S ; radiation coefficient of black body $\text{kcal/m}^2\text{hr}(^{\circ}\text{K}/100)^4$.

In the melting combustion chamber of the slag tap furnace, filled by the flame, there is no mantle gas surrounding the flame, and therefore the flame directly contacts the inner surface of the furnace walls; that is

$$F_F = F_W = F$$

Thus we can simplify Eq. (1) into

$$\frac{Q}{C_e F} = \left[\left(\frac{T_F}{100} \right)^4 - \left(\frac{T_W}{100} \right)^4 \right] \quad (2)$$

where

$$C_e = C_S \left(\frac{1}{\varepsilon_F} + \frac{1}{\varepsilon_W} - 1 \right)$$

Now, this radiation heat Q , absorbed by the furnace walls equals the temperature difference between the heat generated in the furnace and the heat loss by the molten slag, so

$$Q = R_F C_{PR} (t_0 - t_F) - \Delta i \quad (3)$$

where, t_0 and t_F ; the theoretical combustion temperature and flame temperature ($^{\circ}\text{C}$), R_F ; combustion products in the furnace (Nm^3/hr), C_{PR} ; mean specific heat of combustion products between t_0 and t_F ($\text{kcal}/\text{Nm}^3\text{C}$), Δi ; heat loss by the molten slag (kcal/hr). By dividing the above Eq. (3) by $R_F C_{PR}$, we get

$$t_0' - t_F = \frac{Q}{R_F C_{PR}} \quad (4)$$

$$\text{where } t_0' = t_0 - \frac{\Delta i}{R_F C_{PR}}$$

From the right term of the Eq. (4),

$$\frac{Q}{R_F C_{PR}} = \frac{Q}{F} \cdot \frac{F}{R_F C_{PR}} \quad (5)$$

The following equation is obtained for the heat quantity of the molten slag, flowing from the furnace.

$$\Delta i = a \kappa (C_a t_w' + h) \quad (6)$$

where

a : ash content of the fuel (kg/hr)

κ : ash collection factor in the furnace (—)

C_a : specific heat of the molten slag ($\text{kcal}/\text{kg}^{\circ}\text{C}$)

t_w' : temperature of the molten slag ($^{\circ}\text{C}$)

h : fusion heat of ash (kcal/kg)

By assembling all the above equations

$$t_F = t_0' - \frac{\Delta i}{R_F C_{PR}} - C_e \left[\left(\frac{T_F}{100} \right)^4 - \left(\frac{T_W}{100} \right)^4 \right] \cdot \frac{F}{R_F C_{PR}} \quad (7)$$

Laborious work of trial calculation and furnace configurations is required to solve the final Eq. (7). Such complicated processes will be avoided by means of the thermal calculation diagram, Fig. 1.

The explanation of this figure; the surface temperature of furnace wall t_w ① and flame temperature t_F ② are assumed, so $Q/C_e F$ is obtained in the above left corner of Fig. 1 by Eq. (2), and Q/F in the above right corner of the figure by calculating the mean effective radiation coefficient C_e due to Eq. (3), and thus we can reach the point

Fig. 1 Thermal calculation diagram for the slag tap boiler furnace

of ⑥ following the arrow indicated on the diagram.

Conversly, the theoretical combustion temperature t_0 and the heat loss by the molten slag Δi are easily calculated by the combustion condition of the furnace, and thus the diagram is followed from t_0' ④, and $R_F C_{PR}/F$ ⑤ to ⑥, which should agree with the above course.

By following both the upper and lower courses of the diagram, the flame temperature t_F , and the furnace wall surface temperature t_w are determined. The value F of $R_F C_{PR}/F$ is explained in the next section.

3. Simplified design method

Mutual comparison of the slag tap boiler furnaces has been very difficult due to the complicate structure and various configurations. The linear relation between furnace heat release q (kcal/m³hr) and the form factor $f (=F/V_B \text{ m}^2/\text{m}^3)$ was established by A. Zinzen, based on the statistical data for various sorts of melting furnaces. Fig. 2 shows that the value f varies 1.0~3.0 according to $0.5 \sim 2.0 \times (10^6 \text{ kcal/m}^3\text{hr})$ of the value q . Evidence of this tendency is clearly demonstrated by the revised design (2) from the original (1) in Fig. 2.

Generally speaking, the furnace heat release decided by the given combustion condition of fuel air, etc., is defined by the following Eq. (8), which is used for the design of many kinds of furnaces. On the other hand, the furnace form factor is obtained at the same time on the above figure.

Thus the surface area of the furnace inner wall F is calculated by the following Eq. (9).

Lengthy designs in several steps, to secure final drawings of furnace configuration and principal dimensions which for F -value are calculated, are eliminated by this simplified method.

$$q = B(\alpha H_V + \beta V_{LTL} C_{pML}) / V_B \quad \dots\dots\dots (8)$$

$$F = f V_B \quad \dots\dots\dots (9)$$

where

B : fuel consumption (kg/hr)

V_B : furnace volume (m³)

H_V : low calorific value of fuel (kcal/kg)

α : heat release rate of fuel (—)

V_L : total air volume for 1 kg fuel (Nm³/kg)

β : total air rate, supplied to furnaces (—)

t_L : air temperature (°C)

C_{pML} : specific heat of air

4. Slag viscosity

The results of the well-known experiment on the viscosity of coal ash slag by Nicholls and Reid are available, and an amendment to them was recently published by Sage and McIlroy⁽³⁾. These

Fig. 2 Furnace heat release q and form factor f for the slag tap boiler furnace

Fig. 3 Viscosity and temperature characteristics of coal ash slag

investigation results reveal sharp distinction between the molten and the fluid states, by which temperature of critical viscosity, that is, the liquidus temperature, is obtained for the general short slag.

For example, according to the data of Sage and McIlroy, Fig. 3, all the viscosity-temperature curves, except one for long slag, have each distinct critical points (○ mark point), which are shown by a sudden change of curvature. Of these curves, curvatures of fluid state have nearly the same temperature tendencies, which run almost parallel, independent by of slag chemical composition, and thus these curves are easily drawn, when the critical points are given.

The general well-known equation, formulated by Andrade, gives the viscosity-temperature relation for viscoelastic fluids as follows:

$$\eta = A e^{B/T} \quad \dots\dots\dots (10)$$

where T ; absolute temperature (°K), A and B ; constants. Author deduced the following equation instead of the above Andrade formula

$$\eta = \eta_0 e^{-C(t-t_l)} \quad \dots\dots\dots (11)$$

where η_0 ; the viscosity as the critical temperature t_l , C ; constant.

This equation is exclusively applied for the fluidized slag, which is heated above the critical temperature, and the special advantage of this equation is the narrow limited variation of constant C , whose value changes slightly, depending upon the chemical composition of slags.

Now applying the Eq. (11) for the molten slag layer of the slag tap furnace wall, consisting of two kinds of slags molten and solid layer each, we get

$$\eta = \eta_0 e^{-kx} \dots\dots\dots (12)$$

$$k = C \frac{t_w - t_l}{\delta_l} = C \frac{\phi_z}{\lambda_l} \dots\dots\dots (13)$$

where x ; the distance from the boundary of each layer, δ_l the thickness of the liquidized slag, t_w ; its surface temperature, ϕ_z ; the heat flux, λ_l ; its thermal conductivity.

5. The thickness of the liquidized slag layer

Concerning the liquidized slag layer, of which the thickness is dx and the following distance is dz , the following equations are obtained by equilibrium condition of shearing force and weight.

$$\tau' = \tau + \frac{\partial \tau}{\partial x} dx \dots\dots\dots (14)$$

$$\tau' dz - \tau dz + \gamma dx dz = 0 \dots\dots\dots (15)$$

therefore

$$\frac{\partial \tau}{\partial x} = -\gamma \dots\dots\dots (16)$$

On the other hand, from the definition of the viscosity, generally

$$\tau = \eta \frac{\partial w}{\partial x} \dots\dots\dots (17)$$

$$\frac{\partial}{\partial x} \left(\eta \frac{\partial w}{\partial x} \right) = -\gamma \dots\dots\dots (18)$$

Integrating Eq. (18), considering Eq. (3) and the boundary conditions;

$$\left(\frac{\partial w}{\partial x} \right) = 0 \text{ at } x = \delta_l, \quad w = 0 \text{ at } x = 0$$

$$\text{So } \frac{\partial w}{\partial x} = \frac{\gamma}{\eta_0} (\delta_l - x) e^{kx} \dots\dots\dots (19)$$

$$w = \frac{\gamma}{\eta_0 k} [\{ k \delta_l + 1 - kx \} e^{kx} - \{ k \delta_l + 1 \}] \dots\dots\dots (20)$$

Then, the mean flow velocity w_m is calculated from the above equation.

$$w_m = \frac{1}{\delta_l} \int_0^{\delta_l} w dx = \frac{\gamma}{\eta_0 k^3 \delta_l} [2e^{k\delta_l} - (k\delta_l + 1)^2 - 1] \dots\dots\dots (21)$$

Now, mean slag deposit intensity i_m is defined as the deposit as amount on the furnace wall from the coal, so for the steady state

$$i_m z = \gamma w_m \delta_l \quad \therefore \quad \delta_l = \frac{i_m z}{\gamma w_m} \dots\dots\dots (22)$$

and thus

$$ze^{k\delta_l} - (k\delta_l + 1)^2 - 1 = \frac{i_m z}{\gamma^2} \eta_0 k^3 \dots\dots\dots (23)$$

From Eq. (22), the slag layer thickness δ_l is calculated at an arbitrary flowing distance z , measured from the top of the furnace ceiling.

This calculation equation is difficult and the result is not obtainable without trial and error, and so this equation may be simplified by due consideration from the view point of the practical design.

6. Simplified calculation equation

The slag viscosity has important effect upon the calculation of thickness as shown by the above equation. However, its allowable value is limited within the narrow range between 100 and 150 poise, max. 250 poise, due to the operation condition of the slag tap furnace, and so it is sufficient that the simplified equation is applicable for the actual condition. The approximate equation is derived from the above condition as follows.

$$\eta = \frac{A}{t - t_l + B} = \frac{A}{t - D} \dots\dots\dots (24)$$

where t_l : the temperature of critical viscosity, A , B and D : constants. Then

$$\frac{t - t_l}{t_w - t_l} = \frac{x}{\delta_l} \dots\dots\dots (25)$$

Putting Eq. (25) into Eq. (24),

$$\eta = \frac{A}{(t_l - D) + \frac{t_w - t_l}{\delta_l} x} \dots\dots\dots (26)$$

To this Eq. (26), we apply the same procedure as under 5.

$$w_m = \frac{\gamma \delta_l^2}{12A} (t_w + 3t_l - 4D) \dots\dots\dots (27)$$

$$\delta_l^3 = \frac{12i_m z}{\gamma^2} \frac{1}{t_w + 3t_l - 4D} \dots\dots\dots (28)$$

Thus we get a fairly manageable equation as a result.

7. Conclusion

This treatise considered the fundamental theory and design method about the slag tap boiler furnace, and paid special attention to the influence of slag thickness from the thermal engineering point, and showed an applicable method for practical thermal calculation.

Acknowledgement

The author wishes to express his thanks to professor Dr. K. Kawashimo for various advices and guidance.

References

- (1) P. Grasmé: *BWK*, Bd. 8, Nr. 6 (1956), S. 278.
- (2) A. Zinzen: *BWK*, Bd. 11, Nr. 3 (1959), S. 117.
- (3) P. Nicholls and W. T. Reid: *Trans. ASME*, Vol. 62, No. 2 (1940), p. 141; W.L. Sage and J.B. McIlroy: *Trans. ASME*, Ser. A, Vol. 82, No. 2 (1960), p. 145.