Engineering a cyclone pre-furnaces’ calculating method for combustion fine water-coal suspensions

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Abstract. The article is devoted to the method of engineering calculation of the cyclone pre-furnace for incineration of fine coal-water suspensions. This type of device use for ignition and burning fine water-coal suspension. At present there is still no methods allows to make engineering calculations in order to obtain physical damnations of cyclone pre-furnaces for this type of fuels.

1. Introduction
In the foreseeable future, coal will continue to be one of the main energy resources, both in the world and in Russia. It is the most widely available and cheap resource of fossil fuels. The expansion of the technological base of coal use is relevant. One way of use is to provide a fine coal-water suspension (FCWS) for subsequent burning in power plants of wide application, e.g., in the cyclone pre-furnace (CPF). In previous years, many scientists have developed both technologies for creating CWS and researched the features of burning, including in cyclone-type devices. However, there is problem which hampering the development of this technology. The most important of these are the lack of reliable methodological tools for creating the proper cyclone furnaces with guaranteed power characteristics, process parameters, and the complexity of ignition of fuel with high water content.

2. Engineering calculation method
This article discusses the methods producing cyclone-type devices with reliable ignition and combustion of fine water-coal suspensions using a plasma torch.

The developed method has an engineering focus, which determines the proximity of modelling, which is expressed by the following assumptions: quasistationary process; constancy of heat capacities and heat transfer coefficients (Its values correspond to the average process temperature); fuel particles are isothermal; gas mixture is homogeneous; the ash components are inert; only some chemical reactions of interaction with the oxidizing agent are taken into account; It is considered a one-dimensional flow.

Thermal resistance of the fuel particles can be neglected inasmuch as Fourier criterion value $Fo_\theta > 5$ and at the same time the Bio criterion $Bi < 0.5[1–3]$. Such an approach allows analyzing the process and obtaining final expressions suitable for engineering calculations.

The movement of fuel in the form of FCWS inside a cyclone pre-furnace is characterized by physical properties and particle size ($\delta$), cyclone design parameters ($L_o, L, D, \alpha$), the residence time of the particles in the reaction zone ($\tau$) and wall temperature ($T_{wall}$), gas temperature ($T_{gas}$), mixture temperature ($T_{mix}$), particle temperature ($T_{coal}$), as well as the initial fuel temperature ($T_{fuel}$)(Figure 1).
Figure 1. The movement of fuel in a cyclone pre-furnace.

It is assumed that the fuel moves inside some channel. This channel is twisted by forming CPF. In view of this solving a system of equations that takes into account the change in gas temperature, the process of evaporation of moisture from a fuel drop, the temperature change of a fuel particle over time, taking into account the convective-conductive mechanism of heat transfer in the gas mixture, the thermal effect of thermo chemical reactions $\Sigma Q_f$, adopted a methodical approach has the form

$$
T_f = T_{mix} \exp \left( -3BiFo r^{-1} \frac{c_{fuel}}{V_{fuel} C_{fuel}} \right) + T_{wall} \left[ 1 - \exp \left( -3BiFo r^{-1} \frac{c_{fuel}}{V_{fuel} C_{fuel}} \right) \right],
$$

$$
w = 1.25 \frac{w_{fuel}}{\delta_r} \lambda_r \left( T_{mix} - T_{fuel} \right) \left( 1 - w_0 \right) \frac{1}{T_f} \exp \left( -0.33 \right) \tau_w,
$$

$$
T_f = T_{wall} \exp \left( -3BiFo r^{-1} \frac{c_{fuel}}{V_{fuel} C_{fuel}} \right) + T_{fuel} \left[ 1 + \sum \frac{1}{3BiFo r^{-1} T_{fuel} \tau_w} \tau_w \right] \left( 1 - \exp \left( -0.33 \right) \tau_w \right).
$$

(1)

In Eq.(1): $T_{wall}$, $T_{fuel}$, $T_{mix}$—CPF wall temperature, fuel particle temperature and mixture temperature, $w_{fuel}$—particle surface per 1 kg of fuel; $c_{fuel}$, $c_{mix}$ — heat capacity of fuel particles and gas mixture, J/K; $w_0$—fuel initial moisture, %; $\tau_w$—time of evaporation of moisture from the fuel, sec.

The total time of thermo chemical transformations of fuel will be determined by the sum (sec.)

$$
\tau_e = \tau + \tau_w
$$

(2)

The initial temperature of the particles is taken at the temperature of the mixture ($T_{mix}$).

In thermo chemical reactions, the equations describing the release of the components (CH$_4$, CO$_2$, CO, H$_2$, H$_2$O) can be represented as

$$
\frac{dC_j}{d\tau} = \left( C_j^0 - C_j \right) a_j = f_j.
$$

(3)

In Eq.(3) $a_j$—pre-exponential factor.

$$
a_j = K_j \exp \left( -E_j R \frac{1}{T_j} \right)
$$

(4)

$K_j$—component release rate constant (s$^{-1}$) [4–9];

$E_j$—corresponding activation energy in the $j$-th thermochemical reaction (kJ/kμ) [4–9];

$R$—universal gas constant, J/μK;

$C_j^0$—initial concentration of components, mg/m$^3$.

From Eq. (3) find

$$
C_j = C_j^0 \left( 1 - e^{-a_j \tau} \right).
$$

(5)

Another approach to obtain a mathematical model, which will be sufficient for engineering calculations, can be the definition of pyrolysis and combustion processes. These reactions are shown below.
The release of volatile methane is determined by the interaction of the carbon of the coal with the hydrogen released by the heating of the coal:

\[ C + 2H_2 \rightarrow CH_4 + 6.2 \text{MJ/kg}. \]

The release of volatile carbon dioxide is determined by the combustion of carbon when interacting with the released oxygen of the coal:

\[ C + O_2 \rightarrow CO_2 + 33.8 \text{MJ/kg}, \]

and in following up process using CO\(_2\) for partial carbon dioxide gasification of carbon with the formation of CO:

\[ C + CO_2 \rightarrow 2CO - 14.4 \text{MJ/kg}. \]

In addition, the release of volatile carbon monoxide is determined by the oxidation of carbon in coal by oxygen, taking into account the previous use of oxygen for the combustion reaction:

\[ C + O_2 \rightarrow 2CO + 9.4 \text{MJ/kg}. \]

Also, evaporation of moisture and, in this connection, partial steam gasification of semi-coke carbon should be taken into account:

\[ C + 2H_2O \rightarrow CO + H_2 - 10.3 \text{MJ/kg}. \]

The combustion of the formed CO, H\(_2\) and CH\(_4\) is due to the presence of oxygen in the primary and secondary (if necessary) air and passes through the reactions

\[ H_2 + O_2 \rightarrow 2H_2O + 17.8 \text{MJ/kg}, \]

\[ CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 27.8 \text{MJ/kg}, \]

\[ CO + 0.5O_2 \rightarrow CO_2 + 8.9 \text{MJ/kg}. \]

Based on the above approaches and neglect, the calculation algorithm can be represented as follows: first determine the kinetic characteristics of the processes of evaporation of moisture from the FWCS when moving in the pre-furnace in the form of some jet, swirling along the generatrix of the cyclone so that the flame front moves at a linear speed towards the combustion chamber. Then determine the temperature of the fuel particles and the combustion products mixture. At the last stage of the calculations, the design characteristics of the cyclone pre-furnace are determined (Figure 2).

Thus, an approximate physical model of the process of ignition and combustion of FCWS is presented. At first, as the fuel moves in oxidizing environment (air), and then, fuel particles and pyrolysis products ignite and burn. In fact, the cyclone pre-furnace is divided into two parts - the evaporation zone (characterized by \(L_w\)) and the zone of ignition and combustion (characterized by \(L\)), (Figure 1).

Moisture release time is found to determine the design characteristics of CPF (in sec.):

\[
\tau_w = \frac{W'}{1.25 \cdot w_f \cdot \frac{6}{P_p} \cdot \frac{T_{wall} - T_{fuel}}{h_{sup}} \cdot (1 - W')^{1.67} \cdot (W')^{0.33}}.
\]  

(6)

Then determine the length of the evaporation section, m

\[
L_w = \frac{V_{sup} \cdot G}{\pi \cdot d^2} \cdot \tau_w.
\]  

(7)
Figure 2. Algorithm engineering calculation of CPF.

also determine the full length of the pre-furnace, given that the flow is twisted

\[ L = 2 \cdot d \cdot \frac{\pi \cdot D}{4} \left[ \frac{\sqrt{(D \cdot \tan \alpha)^2 + D^2}}{D} \right] \] (8)

In these equations (8):

- \( W \) – fuel moisture;
- \( w_f \) – correction factor for the speed of particles flurries;
- \( \rho_p \) – particle density, kg/m³;
- \( \delta \) – characteristic of particle size;
- \( \alpha \) – flow entry angle;
- \( T_{wall} \) – CPF wall temperature, °C;
- \( T_{fuel} \) – fuel temperature, °C;
- \( h_{vap} \) – vapor enthalpy, kJ/kg;
\( V_{\text{vap}} \) – volume of steam in the combustion products, \( \text{m}^3/\text{kg} \);

\( G \) – steam consumption, \( \text{kg/s} \);

\( \ell_{\text{burn}} \) – correction factor to the length of the torch when burning FCWS;

\( \omega_{\text{mix}} \) – velocity of the mixture (combustion) at the flow axis, \( \text{m/s} \);

\( \tau \) – characteristic of length, \( \text{m} \);

\( D \) – torch twist diameter, \( \text{m} \);

\( \text{tg}\alpha \) – twist angle.

3. The analysis of the combustion characteristics’ influence on the cyclone pre-furnace construction

Based on the calculations results the dependences of gaseous products release of pyrolysis and combustion of FCWS are obtained (Figure 3).

![Figure 3. Comparison of the results with experimental and calculated data on the pyrolysis of carbon-containing fuels [10–15].](image)

The adequacy of the model is noted in comparison with the experimental data of other authors [10–15]. It was established that due to the complete hydrogen burning into the fuel in the initial part of the process (0…1s), a high temperature of the mixture (\( T_{\text{mix}} \)) is provided up to 1800–2500 K. The moisture release time for heat-stressed pre-furnaces is less than 2s, and for refrigerated ones it can be up to 5s.

The characteristic area of evaporation, depending on the flow rate, can be 2.5–200 m (Figure 4).
Figure 4. The section length dependence of flow velocity.

Pre-furnace efficiency affects the length of the section. So for pre-furnaces with a capacity of 2 and 8 MW, the length $L_w$ is 2.3–2.4 times less for more powerful CPF (Figure 3). It is shown that the length of the coil inside the cyclone is almost independent of its efficiency (Figure 5).

Figure 5. The efficiency effect on CPF size for $\omega_{mix}=20$ m/s.

It can be seen that the influence of temperature is less noticeable than the influence of CPF efficiency on its linear dimensions. If we take the cyclone diameter of 1–1.5 m with burning capacity of 8–16 MW, then the length of the apparatus is 4.5–10 m (Figure 7).

In general, the pre-furnace can be designed with different ratios of its length (L) to diameter (D) (Figure 6).
Figure 6. The linear dimensions of CPF depending on its efficiency and reaction for $\omega_{mix}=20$ m/s.

Figure 7. Constructive characteristics of CPF depending on its efficiency ($\alpha=6–17^{\circ}$).

4. Summary
Thus, the article presents a technique to calculate the geometric parameters of a cyclone pre-furnace for burning FCWS. The effect of kinetic processes on the physical design of the apparatus is shown. Graphic dependences of various factors are given, such as the speed of the mixture, the angle of fuel injection, the diameter of the flow twist on the diameter and the length of the cyclone pre-furnace. The adequacy of the proposed method is shown by comparison with the calculations and experimental values of other researchers.

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