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Designing for Long Campaign Life Blast Furnace (1) —The Mathematical Model of Temperature Field for Blast Furnace Lining and Cooling Apparatus and New Concept of Long Campaignship Blast Furnace Cooler Design

Susen Cheng[1], *Qingguo Xue*[1], *Weiguo Yang*[2], *Maolin Wu*[1], *Tianjun Yang*[1]

1) Metallurgy School, University of Science and Technology Beijing, Beijing 100083, China
2) Ironmaking Department, Bejing Central Engineering and Incoporation of Iron and Steel Industry, Bejing, 100053, China

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Abstract: The physical and mathematical model of temperature field for blast furnace stave coolers was established. The computation results show that the heat resistance of 2 -6 mm water scale within the cooling pipe is about 7%-20% of the total heat resistance of cooling stave body, as for drilling duct type, the heat resistance of 2-6 mm water scale is about 88%-98% of the total heat resistance. Using drilling duct or full cast pipe can eliminate gas clearance and coating layer between pipes and cast iron body and reduce the heat resistance of the cooler sharply and improve the coefficient of heat transfer to a great extent. The water velocity within coolers can be kept at the level of 0.5-1.5 m/s, the higher water velocity can not decrease the hot surface temperature, but can increase energy consumption for cooling water.

Key words: blast furnace; cooler; mathematical model; heat resistance; water velocity

If cooling water is scale-free, Blast Furnace (BF) campaign life is mainly determined by the cooler campaign life. The life of cooling apparatus can be determined by its design, manufacture, maintenance and so on, but its design is the foundation of long campaign life stave coolers. High temperature and temperature wave inside cooler are one of the most important conditions that the cooler is destroyed. In according with the temperature profile inside BF cooler, the temperature and temperature wave can be reduced by changing the structural parameters of BF coolers. Obviously, the numerical simulation of cooler temperature field can show the suitable structural parameters of BF coolers. In this paper, the controlling equation and boundary conditions of BF cooler temperature field are discussed seriously.

Most BF operators are used to judge the cooler condition by heat flux into BF wall which is computed to use water temperature difference of the cooling pipe inlet and outlet. For this point of view, some of our ideas were given. The new concept of cooler design was put forward by analyzing the coefficient of heat convection between stave body and cooling water within cooling pipe in the conventional cooling stave with cast steel cooling pipes in cast iron body.

1 Selection of Cooler Physical Model and its Discretization for Calculation

Because cooler apparatus is among lining or slag skull, filling material and furnace shell, it is difficult to decide boundary condition of the cooler apparatus itself, so the physical model of stave cooler (**figure 1**) is designed. Because the physical model includes round cooling pipe, considering the precision of the calculation result, it should be made discretization into irregular hexahedron for fitted body.

2 Selection of Controlling Equation for Calculation

The three-dimension heat transfer equations based on energy balance are suitable for our physical model. The three-dimension heat transfer equations are

(1) Steady condition.

$$\frac{\partial}{\partial x}(\lambda(T)\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda(T)\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(\lambda(T)\frac{\partial T}{\partial z})=0.$$

(2) Unsteady condition.

$$\frac{\partial}{\partial x}(\lambda(T)\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda(T)\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(\lambda(T)\frac{\partial T}{\partial z})=\rho c_P\frac{\partial T}{\partial \tau}.$$

where τ is the computing time, s; $\lambda(T)$ the thermal conductivity at temperature T, (the thermal conductivity for common boundary is equal to the harmonic mean of thermal conductivity of two neighboring layers), W/(m·K); x, y, z the length along the direction of three space coordinate axes, respectively, m; T the temperature of the physical model, K; ρ the density of the physical model, kg/m^3; c_p the thermal capacity, J/(kg·K).

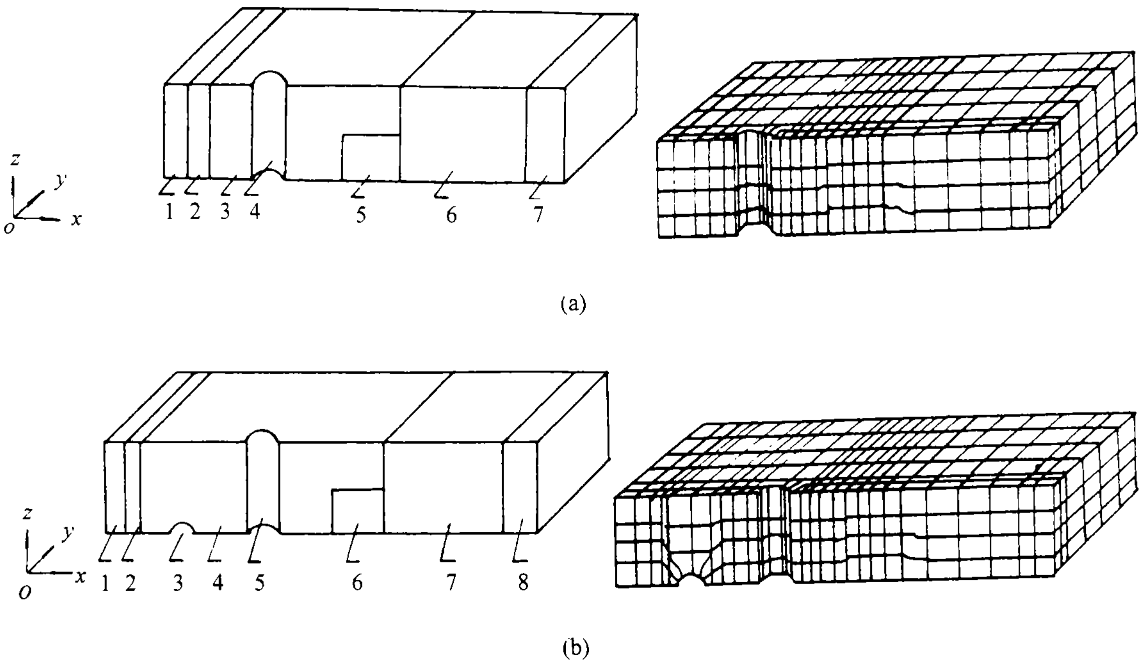

Figure 1 Physical model of stave cooler and its discretization, (a) Stave cooler with single cooling steel pipes, 1– furnace shell, 2– filling material, 3– stave body, 4– cooling steel pipe, 5– inlaid brick, 6– lining, 7– slag skull; (b) stave cooler with double cooling steel pipes, 1– furnace shell, 2– filling material, 3– S cooling steel pipe, 4– stave body, 5– U cooling steel pipe, 6– inlaid brick, 7– lining, 8– slag skull.

(3) Parameters for calculation.

The parameters for calculation are listed in **table 1** [1].

Table 1 Parameters for Calculation

Item	furnace shell	filling matial	cooling stave	cooling plate	refractory
material	carbon	casting refractory	nodular cast iron	copper	SiC brick
thermal conductivity / W/(m·K)	$52.5-0.025\,T$	0.35	$42.05-0.0268\,T$	$385-0.04\,T$	$17-0.009\,T$
calculated dimension/m	0.04	0.04	thickness of rib 0.075	thickness of wall 0.012 water duct 0.04×0.08	thickness of inlaid brick 0.075 depth of inlaid brick 0.07

3 Boundary Condition

3.1 Boundary condition of inner surface of BF wall

The gas flow temperature is assumed 1200 ℃, the coefficient of heat convection between furnace wall and hot gas flow is

$\alpha_1=232\ \mathrm{W/(m^2\cdot K)}$.

3.2 Boundary condition of external surface of BF wall (furnace shell)

The temperatures of furnace shell and heat flux through furnace shell change with the conditions inside BF, but the atmospheric temperature is known and the coefficient of heat convection between the external surface of furnace shell and atmosphere can be gotten by empirical formula. The atmospheric temperature is assumed 30 ℃, the coefficient of heat convection between furnace shell and atmosphere is

$\alpha_2=9.3+0.058\,T\quad \mathrm{W/(m^2\cdot K)}$

where T is the temperature of furnace shell.

3.3 The boundary condition of symmetry plane

Because of a three dimension model, the heat flux equals to zero in the two sides of symmetry plane. It may consider that the boundary conditions for symmetry planes along the peripheral direction and axial direction of BF are of adiabatic condition, *i.e.*

$q=0$.

where q is the heat flux into symmetry plane, W/m^2.

3.4 Heat convection between cooling water and stave body

Heat transfer between cooling water and stave body contains five types: (a) by radiation; (b) by conduction of the clearance between stave body and cooling water pipes; (c) by conduction of a ceramic coat for preventing carbonization on the external surface of the cooling water pipe ; (d) by conduction of the cooling water pipes wall; (e) by forced convection between cooling water and the cooling water pipe. Heat transfer by radiation in the clearance is a nonlinear function of the temperature T and the coat is so thin, it can lead the codes to divergence, so a synthetic heat transfer coefficient is given by the analysis of all over the heat resistance above.

The heat convection resistance among cooling water and the wall of the pipe, conducting resistance of the pipe wall, conducting resistance of the coat and radiation resistance in the clearance will be included in the heat resistance between water and stave body.

(1) The convection heat resistance between cooling water and inner surface of steel pipe R_α is

$$R_\alpha=\left(\frac{1}{\alpha_3}\right)\left(\frac{d_o}{d_i}\right),$$

where α is the coefficient of heat convection between cooling water and steel pipe, W/(m^2·K); d_o the external diameter of the steel pipe, m; d_i the inner diameter of the steel pipe, m.

Because of forced convection, α_3 can be calculated through the following equation

$$Nu=\frac{\alpha_3 d_i}{\lambda}=0.023\,Re^{0.8}Pr^{0.4},$$

$$\alpha_3=0.023\frac{v^{0.8}\lambda^{0.6}c_P^{0.4}\rho^{0.4}}{d_i^{0.2}\upsilon^{0.4}},$$

where v is the cooling water velocity, m/s; λ the thermal conductivity, W/(m·K); c_P the specific heat capacity at constsnt pressure, J/(kg·K); ρ the density, kg/m^3; υ the kinetic viscosity of cooling water, m^2/s.

(2) The conductive resistance of the steel pipe wall is

$$R_w=\frac{d_o}{2\lambda_w}\ln\frac{d_o}{d_i}$$

where λ_w is the thermal conductivity of the steel pipe wall, W/(m·K).

(3) Heat transfer resistance of the coating layer on the external surface of the cooling water pipe R_c.

This coating layer is for preventing carbonization on the external surface of the cooling water pipe, its thickness is determined by casting technology, generally 0.2–0.7 mm. Because the layer is rather thin, it can be treated as a plane plate conductive heat transfer, as

$$R_c=\frac{\delta_c}{\lambda_c}.$$

where δ_c is the thickness of the coating layer, m; λ_c the thermal conductivity of the coating layer, W/(m·K).

(4) Heat resistance of the gas clearance between the cooling water pipe and stave body R_g.

This heat resistance is formed during solidification, it is just a gas clearance with a thickness of 0.1 – 0.3 mm, it can also be treated as a plane plate. However, there is both heat transfers by conduction and radiation. For treating heat transfer by radiation, it may be simplified; an equivalent heat resistance R_g [1] can be used

$$R_g=\frac{\delta_g}{\lambda_e}.$$

where λ_e is the equivalent thermal conductivity of the gas clearance, W/(m·K).

$$\lambda_e=\lambda_g+C_0\varepsilon_{sy}\theta\delta_g.$$

here

$$\varepsilon_{sy}=\frac{1}{\frac{1}{\varepsilon_s}+\frac{1}{\varepsilon_c}-1},$$

$$\theta=\frac{\left(\frac{T}{100}\right)^4-\left(\frac{T_c}{100}\right)^4}{t-t_c},$$

where λ_g is the gas thermal conductivity, W/(m·K); δ_g the thickness of the gas clearance, m; ε_s, ε_c the emissivity of stave body and coating layer; t, t_c the temperature of the surface of stave body close to the coating layer and the temperature of the coating layer surface, ℃.

$T=t+273$ (K), $T_c=t_c+273$ (K);

C_0, planck constant, 5.67 W/(m^2·K^4).

(5) The conductive resistance of the layer of cooling water scale on the inner surface of cooling water pipes is

$$R_s=\frac{d_{so}}{\lambda_s}\ln\frac{d_{so}}{d_{is}},$$

where d_{so}, d_{is} is the external diameter and the inner diameter of the layer of water scale, m; λ_s the thermal conductivity of water scale, W/(m·K). So the total heat resistance R between cooling water and stave body equals to

$$R=R_\alpha+R_w+R_c+R_g+R_s,$$

and the heat transfer coefficient h_w [3] is

$$h_w=\frac{1}{R}=$$

$$\frac{1}{\left(\frac{1}{\alpha}\right)\left(\frac{d_o}{d_i}\right)+\left(\frac{d_o}{2\lambda_w}\right)\ln\frac{d_0}{d_i}+\frac{\delta_c}{\lambda_c}+\frac{\delta_g}{\lambda_e}+R_s} \qquad (1)$$

(6) The selection of parameters for calculation.

$d_o = 0.07$ m, $d_i = 0.058$ m, $\upsilon = 1.5$ m/s, $\lambda = 50$ W/(m·K), $c_P = 4170$ J/(kg·K), $\rho = 998$ kg/m^3, $\nu = 0.659\times10^{-6}$ m^2/s, $\lambda_g = 0.0385$ W/(m·K), $\delta_g = 0.15$ mm, $\varepsilon_s = \varepsilon_c = 0.8$, $t_w = 40$ ℃, $t_c = 80$ ℃, $\delta_c = 0.2$ mm, $\lambda_s = 0.6$ W/(m·K).

(7) Analysis for the results of calculation.

As there is no water scale on the inner surface of the cooling pipe, the heat resistance and convection heat transfer coefficient[2, 3]are:

$\alpha_3 = 5641$ W/(m^2·K); R_a=0.213 94 × 10^{-3} m^2·K/W; R_w= 0.132×10^{-3} m^2·K/W;R_c= 0.25×10^{-3}m^2·K/W;R_g= 3.669 × 10^{-3} m^2·K/W; R=4.265 × 10^{-3} m^2·K/W; h_w= 234.5 × 10^{-3} W/(m^2·K).

According to the results and experiments, the heat transfer coefficient between cooling water and stave body can be determined by formula

$\alpha_3 = 208 + 47.5\,V$ W/(m^2·K)

where V is the cooling water velocity, m/s.

4 New Concept of Long Compaign Stave Design

(1) Analysis of the heat resistance of stave. As it is free of water scale within the cooling water pipe, the heat resistance of the gas clearance hold 86%, of coating layer hold 5.86%, of convection hold 5.02%, of the total resistance of the stave body. As the gas clearance from 0.25 mm down to 0.1 mm, the total heat resistance lower down to a great extent,and h_w will increase 110%. It is clear that in the manufacturing process of cooling stave, to decrease the gas clearance is very important. This is why a drilling duct stave or full cast stave is put forward.

For drilling duct and full cast stave,

$\delta_g = 0$, $\delta_c = 0$, R_w= 0, R_g= 0, R_c=0,R=0.17 727 × 10^{-3} m^2·K/W; $h_w = \alpha_3$= 564 1 W/(m^2·K).

The heat transfer coefficient of drilling duct or full cast stave is 24 times as much as that of cast pipe stave.

(2) The influence of water scale on cooling capacity.

(a) For cast pipe stave.

As there is water scale on the inner surface of cooling water pipe, then

δ_s= 1 mm,R_s=1.666 6 × 10^{-3} m^2·K/W,R=5.931 5 × 10^{-3} m^2·K/W, h_w= 168.5 W/(m^2·K);

δ_s= 2 mm, R_s= 3.333 3 × 10^{-3} m^2·K/W, R = 7.598 3×10^{-3} m^2·K/W, h_w= 131.6 W/(m^2·K);

δ_s= 3 mm, R_s= 5 × 10^{-3} m^2·K/W, R = 9.265 × 10^{-3} m^2·K/W, h_w= 107.9 W/(m^2·K);

δ_s=5mm, R_s=8.3333×10^{-3}m^2·K/W, R = 12.598 3×10^{-3} m^2·K/W, h_w= 79.37 W/(m^2·K).

If there are 1mm, 2mm, 3mm or 5mm thickness of water scale within cooling pipe, the heat transfer coefficient between cooling water and stave body will reduce 28%, 44%, 66% in contrast with that there is scale free water within the cooling water pipe.

(b) For drilling duct stave.

As there is water scale within the drilling duct,

δ_s= 1 mm,R_s= 1.666 6 × 10^{-3} m^2·K/W,R = 1.84387×10^{-3} m^2·K/W, h_w= 542.33 W/(m^2·K);

δ_s=2 mm, R_s= 3.3333 × 10^{-3} m^2·K/W, R=3.51057× 10^{-3} m^2·K/W, h_w=284.85 W/(m^2·K);

δ_s=3mm, R_s=5 × 10^{-3} m^2·K/W, R=5.17727×10^{-3} m^2·K/W, h_w=193.15 W/(m^2·K);

δ_s= 5 mm, R_s= 8.333 3×10^{-3}m^2·K/W,R = 8.506 07×10^{-3} m^2·K/W, h_w= 117 W/(m^2·K).

If there are water scale of 1 mm, 2 mm, 3 mm, 5 mm thickness within the cooling duct, the heat transfer coefficient will reduce 90%, 95%, 97%, 98% in contrast with that there is free of water scale within drilling duct.

So it is evident that the quality of cooling water makes important influence on the heat transfer capability of cooling apparatus. It can cause burnout of coolers.

Therefore, as mentioned above, no matter what stave with water scale it is, the heat transfer capability can not be improved evidently.

As for water scale, most BF operators understand its harmful effect, it can be taken away through ordinary water treatment technology. Therefore, how to eliminate this gas clearance becomes an important idea in designing. This kind of idea is really established through heat transfer modeling. It is to use drilling duct in a copper or steel body to replace cast steel pipe into iron body.

In industrial practice, Germany put stress on copper staves, some Chinese researchers put stress on steel staves. Their considerations are concentrated on the thermal conductivity of material. Here our modeling shows the important idea—the heat resistance of gas clearance should be eliminated.

As a simple summery, a drilling duct stave cooler is of a new generation to replace the conventional stave cooler with cast steel pipe.

5 Influence of Water Velocity on Heat Transfer Capability of Cooling Apparatus

(1) For stave with cast steel cooling pipes. In equation (1) as water velocity $V \to \infty$,

$h_w \to 1/(R_W + R_C + R_g + R_s)$,

i.e. h_w is determined by the heat resistance of pipe wall, coating layer, gas clearance and water scale.

(2) For stave with drilling duct. If a drilling duct stave with water scale inside duct is applied, as water velocity $V \to \infty$, then

$h_w \to 1/R_S$,

and as free of scale, then

$h_w \to \infty$.

As for the stave cooler with cast steel pipe in cast iron stave body, the h_w does not change rapidly with the velocity of cooling water, but for drilling duct stave free of water scale, the result turned out contrary to that.

6 Conclusions

(1) The physical and mathematical model of temperature field for BF stave coolers was established. The synthetic coefficient of heat transfer between cooling water and stave body, instead of heat convection coefficient between cooling water and cooling water pipe, is used to compute coolers temperature profile, it can avoid computational program to diverge and complex calculation and improved calculation precision.

(2) Water scale within pipe is just an isolating layer. the heat resistance of 2–6 mm water scale is about 7%–20% of the total heat resistance of cast iron stave body with cast steel pipe; the heat resistance of 2–6 mm water scale is about 88%–98% of its total heat resistance of the stave body with drilling duct. For cooling intensity of cooler, the quality of cooling water is importance first and then cooler. So a scale free water treatment is of most necessary.

(3) Using drilling duct or full cast pipe (it is cheaper and easier to make a full cast pipe) to replace cast steel pipe in coolers, which can eliminate gas clearance and coating layer between pipes and cast iron body. This technology can reduce the heat resistance of the cooler sharply and improve the coefficient of heat transfer largely. This will also be a new generation of cooler for long campaignship BF.

(4) Water velocity within coolers can be kept at the level of 1.0–1.5 m/s. The higher velocity can not decrease the hot surface temperature but increase energy consumption for cooling.

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Reference

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