Heat Transfer Analysis of Blast Furnace Stave Based on Entransy Theory

X Xu¹², L j Wu¹
¹ Department of Thermal Engineering, School of Mechanical Engineering, TongJi University, Shanghai 201804, China
² Nantong University Xinglin College, Jiangsu Nantong 226000, China
xinshoux2@126.com

Abstract. Based on entransy theory, the entransy balance equation and the entransy dissipation of blast furnace stave are obtained. The thermal resistance of blast furnace stave is defined. It is proposed to combine the maximum temperature of the hot surface and the thermal resistance to evaluate the heat transfer performance of the cooling stave. They represent the thermal safety and the overall heat transfer performance of the cooling stave respectively. The calculation method of the thermal resistance of blast furnace stave is illustrated with a practical example. The influence of the radius of the water pipe, the water pipe interval and the shape of the water pipe on the maximum temperature and the thermal resistance of the cooling stave is discussed. The results show that the maximum temperature and thermal resistance of the cooling stave have different changing tendency with the influence of different factors. In the optimization design of the blast furnace stave, the design scheme with smaller thermal resistance can be chosen on the premise of ensuring thermal safety, so as to improve the overall heat transfer performance.

1. Introduction
Blast furnace stave is an important cooling equipment installed in the blast furnace. Its heat transfer performance is of great significance to the production safety of the blast furnace and the efficient utilization of energy. Many scholars have made deep research on the heat transfer analysis of the blast furnace stave. The influence of various factors on the temperature distribution of the cooling stave are discussed⁰⁵. In most of these studies, the maximum temperature of the cooling stave is used as an index to evaluate the heat transfer performance. However, the maximum temperature of the cooling stave, as a local parameter, can be used to evaluate the thermal safety of the cooling stave, but it does not reflect the overall heat transfer performance of the cooling stave. Therefore, a physical quantity which reflects the overall heat transfer performance of the cooling stave should be sought, together with the maximum temperature of the cooling stave, to be used as the evaluation index of the heat transfer performance of the blast furnace stave.

To reflect the overall heat transfer performance of the system, Guo et al. ⁶ defined the physical quantity ‘entransy’ which represents the heat transfer capacity, and proposed the entransy dissipation extremum principle. Many scholars have conducted the research on the optimization of heat transfer with the minimum entransy dissipation as the target ⁷¹³. In the optimization of a heat conduction process, Cheng et al. ¹⁴ proposed the minimum thermal resistance principle. The smaller the equivalent thermal resistance, the better the overall heat transfer performance of the system is. In this paper, the entransy theory is applied to the heat transfer analysis of the blast furnace stave. The
entransy balance equation and the entransy dissipation of the stave are obtained. On this basis, the thermal resistance of the blast furnace stave is defined. It can be used as the evaluation index of the overall heat transfer performance of the cooling stave. The calculation method of the thermal resistance of blast furnace stave is illustrated with a practical example. The influence of the radius of the water pipe, the water pipe interval and the shape of the water pipe on the maximum temperature and the thermal resistance of the cooling stave is discussed.

2. **Entransy theory summary**

Entransy is a physical quantity describing heat transfer ability. It is defined

\[ E_h = \frac{1}{2} Q_{Vh} T \]  

(1)

where \( Q_{Vh} \) is the thermal energy stored in an object of constant volume, J, and \( T \) is the temperature of the object, K.

The dissipation of entransy per unit time and per unit volume, \( \phi_h \), is called the entransy dissipation function.

\[ \phi_h = -\dot{q} \cdot \nabla T \]  

(2)

where \( \dot{q} \) is the heat flux vector, W·m\(^{-2}\), and \( \nabla T \) is the temperature gradient, K·m\(^{-1}\).

For three-dimensional problems, the entransy dissipation of the whole volume is

\[ E_{vd} = \int \phi_h dV \]  

(3)

On this basis, the equivalent thermal resistance of the three-dimensional heat conduction problem is defined as

\[ R_e = \frac{E_{vd}}{Q_{vs}} \]  

(4)

where \( E_{vd} \) is the entransy dissipation, W·K, and \( Q_{vs} \) is the total heat flow on the boundary, W.

The minimum thermal resistance principle can be expressed as follows, for the heat conduction problem with certain constraint conditions, if the equivalent thermal resistance of the object is the minimum, the thermal conductivity of the object is the best.

3. **The equivalent thermal resistance of the blast furnace stave**

The simplified model of the blast furnace stave can be regarded as a three-dimensional steady state heat conduction, which is shown in Figure 1.

![Figure 1. Three-dimensional graph of blast furnace stave](image)

The heat flow of each surface is

\[ \dot{Q}_i = \int \dot{q}_i dA_i \]  

(5)

where \( \dot{q}_i \) is the heat flux on each surface element, W·m\(^{-2}\), \( A_i \) is the area of each surface, m\(^2\).

The relationship of the heat flow of each surface is
\[ \dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3 \] (6)

where \( \dot{Q}_1 \) is the input heat flow from the hot surface, \( \dot{Q}_2 \) is the output heat flow from the cold surface, \( \dot{Q}_3 \) is the output heat flow from the inner surface of the cooling water pipes. The input heat flow from the hot surface is equal to the sum of the output heat flow from the cold surface and the inner surface of the cooling water pipes.

The entransy flux of each surface is
\[ \dot{E}_{wi} = \int \dot{q}_i T_i dA_i \] (7)

where \( T_i \) is the temperature of each surface element, K.

The input entransy flux is not equal to the output entransy flux in the blast furnace stave because of the entransy dissipation in the process of heat transfer. Their relationship is
\[ \dot{E}_{w1} = \dot{E}_{w2} + \dot{E}_{w3} + \dot{E}_{wh} \] (8)

where \( \dot{E}_{w1} \) is the input entransy flux from the hot surface, W·K, \( \dot{E}_{w2} \) is the output entransy flux from the cold surface, W·K, \( \dot{E}_{w3} \) is the output entransy flux from the inner surface of the cooling water pipes, W·K, \( \dot{E}_{wh} \) is the entransy dissipation of the blast furnace stave, W·K. Equation (8) is the entransy balance equation of three-dimensional steady-state heat conduction of the blast furnace stave. The input entransy flux of the blast furnace stave is equal to the sum of the output entransy fluxes and the dissipated entransy.

The equivalent thermal resistance of the blast furnace stave is equal to the entransy dissipation divided by the square of the heat flow:
\[ R = \frac{E_{wh}}{Q^2} = \frac{E_{wh}}{Q^2} \] (9)

The thermal resistance of the blast furnace stave can be used as an evaluation index of the whole heat transfer performance. The smaller the thermal resistance, the better the overall heat transfer performance is.

4. Heat transfer analysis of the blast furnace stave

4.1. Calculation of the thermal resistance of a blast furnace stave

The blast furnace of an experiment was selected as the research object. The thickness of the stave is 0.2 m, the width is 0.6 m, and the height is 1 m. The physical properties of cast steel for cooling stave material are as follows: the density is 7800 kg·m⁻³, the thermal conductivity is 52 W·m⁻¹·K⁻¹, and the specific heat at constant pressure is 486 kJ·kg⁻¹·K⁻¹.

The steady-state heat transfer of blast furnace stave can be regarded as a heat conduction problem. The three-dimensional steady state heat conduction differential equation is
\[ \frac{\partial}{\partial x} (\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (\lambda \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (\lambda \frac{\partial T}{\partial z}) = 0 \] (10)

where \( T \) is the temperature, K, \( \lambda(T) \) is the thermal conductivity when the temperature is \( T \), W·m⁻¹·K⁻¹, \( x, y, z \) are the directions of the thickness, width and height of the stave respectively.

The heat exchange between the cold surface and the ambient air is the third kind boundary condition. The temperature of the air is 30 °C, and the natural heat transfer coefficient between the cold surface and the ambient air is 11 W·m⁻¹·K⁻¹. The heat exchange between the cooling water and the cooling stave is the third kind boundary condition. The temperature of the cooling water is 30 °C. The calculation result shows that it is the turbulent flow with forced convection heat transfer in the pipe. The convective heat transfer coefficient between the cooling water and the inner surface of the water pipe is \[{15}\]
\[ h_{wb} = 0.023v^{0.8}\lambda_s^{0.4}P_r^{0.4}d_i^{-0.2}v^{-0.8} \] (11)
where $d_1$ is the equivalent diameter of the cooling water pipe, m; $v$ is the cooling water velocity in the pipe, $m\cdot s^{-1}$; $\lambda_w$, $\nu$, and $Pr$ are the thermal conductivity, $W\cdot m^{-1}\cdot K^{-1}$; Kinematic viscosity, $m^2\cdot s^{-1}$; and Prandtl number of the water at 30 °C respectively.

The heat exchange between the gas and the hot surface of the blast furnace stave is complicated. There are two forms of heat exchange, convection and radiation. The composite heat transfer coefficient between the gas and the hot surface of the stave is $232~W\cdot m^{-1}\cdot K^{-1}$[16]. The gas temperature in the laboratory furnace is 400 °C.

The three-dimensional heat transfer model of the blast furnace stave was evaluated using the finite element software ANSYS. The temperature field of the cooling stave was obtained by ANSYS calculation.

The entransy flux on the hot surface, cold surface, and inner surface of the cooling water pipes can be calculated as follows:

$$\dot{E}_h = \sum_{i=1}^{n} q_i T_i a_i$$  \hfill (12)

where $\dot{q}_i$ is the heat flux of each node on each surface, $W\cdot m^{-2}$; $T_i$ is the temperature of each node on the surface, K; $a_i$ is the area occupied by each node, $m^2$; and $n$ is the number of nodes of each surface.

The temperature of each node are brought into equation (12) and calculated, the input entransy flux on the hot surface $\dot{E}_{h1}$, the output entransy flux on the cold surface $\dot{E}_{h2}$, and the output entransy flux on the inner surface of the cooling water pipe $\dot{E}_{h3}$ can be obtained respectively. $\dot{E}_{h1}$, $\dot{E}_{h2}$, $\dot{E}_{h3}$ are brought into equation (8), (9) and calculated, the entransy dissipation $\dot{E}_{mp}$ and the thermal resistance of the blast furnace stave $R_h$ can be obtained.

4.2. Effect of the radius of the cooling water pipe on the maximum temperature of the hot surface and the thermal resistance of the stave

The overall structural parameters of the cooling stave are set unchanged. Two cooling water pipes are evenly arranged with the interval of 300mm, and the cooling water velocity is 2m/s. The maximum temperature of the hot surface and the thermal resistance of the stave are calculated with different radius of the cooling water pipe. The results are shown in Figure 2.

![Figure 2. Effect of the radius of the cooling water pipe on the maximum temperature of the hot surface and the thermal resistance of the stave](image-url)

The maximum temperature of the hot surface and the thermal resistance of the cooling stave decreased rapidly with the increase of the radius of the water pipe. When the radius of the pipe is increased from 20mm to 60mm, the maximum temperature of the hot surface is decreased by 45°C, and the decrease rate is 23.3%. The corresponding thermal resistance decreased by 47.2%. This shows that increasing
the radius of the cooling water pipe can effectively improve the thermal safety and the overall heat transfer performance of the cooling stove.

4.3. Effect of the cooling water pipe interval on the maximum temperature of the hot surface and the thermal resistance of the stave

The overall structural parameters of the cooling stave are set unchanged. The cooling water velocity is 2m/s, and the radius of the pipe is 0.02m. The maximum temperature of the hot surface and the thermal resistance of the stave are calculated with different intervals of the cooling water pipe (2 cooling water pipes arranged with the interval of 300mm; 3 cooling water pipes arranged with the interval of 200mm; 4 cooling water pipes arranged with the interval of 150mm; 5 cooling water pipes arranged with the interval of 120mm). The results are shown in Figure 3.

![Figure 3](image)

**Figure 3.** Effect of the cooling water pipe interval on the maximum temperature of the hot surface and the thermal resistance of the stave

The maximum temperature of the hot surface and the thermal resistance of the cooling stave decreased rapidly with the decrease of the water pipe interval. When the water pipe interval is decreased from 300mm to 120mm, the maximum temperature of the hot surface is decreased by 46°C, and the decrease rate is 23.8%. The corresponding thermal resistance is decreased by 32.1%. This shows that decreasing the interval of the cooling water pipe can effectively improve the thermal safety and the overall heat transfer performance of the cooling stave.

In comparison with figure 3, it is found that with the same thermal resistance decline, reducing the cooling water pipe interval can reduce the maximum temperature of the hot surface more effectively, thus improving the thermal safety of the cooling stave; while with the same thermal maximum temperature drop, increasing the radius of the cooling water pipe can reducing the thermal resistance more effective, thus improving the overall heat transfer performance of the cooling stave.

4.4. Effect of the shape the cooling water pipe on the maximum temperature of the hot surface and the thermal resistance of the stave

The overall structural parameters of the cooling stave are set unchanged. The 2 cooling water pipes are evenly arranged with the interval of 300mm, the radius of the pipe is 0.02m, and the cooling water velocity is 2m/s. Then the cooling water pipe was changed from circular to elliptical with the same surface area. The maximum temperature of the hot surface and the thermal resistance of the stave are calculated with different ratios of the minor axis to major axis \((a/b)\) of the elliptical pipe. The results are shown in Figure 4.

The maximum temperature of the hot surface and the thermal resistance of the cooling stave increased slowly with the decrease of \(a/b\), and the curve becomes steep when the ratio \((a/b)\) is less than 0.7. When the ratio \((a/b)\) is decreased from 1(circular pipe) to 0.7, the maximum temperature of the hot surface increased by 3°C, and the increase rate is 1.6%. The corresponding thermal resistance increased
by 4.3%. When the ratio $(a/b)$ is decreased from 0.7 to 0.5, the maximum temperature of the hot surface increased by 7°C, and the increase rate is 3.6%. The corresponding thermal resistance increased by 5.3%. This shows that changing the shape of the cooling water pipe from circular to elliptical with the same surface area will reduce the thermal safety and the overall heat transfer performance of the cooling stave.

**Figure 4.** Effect of the shape the cooling water pipe on the maximum temperature of the hot surface and the thermal resistance of the stave

5. Conclusions
In this paper, the entransy theory is applied to the heat transfer analysis of the blast furnace stave. The entransy balance equation and the entransy dissipation of the stave are obtained. The thermal resistance of the blast furnace stave is defined. It can be used as the evaluation index of the overall heat transfer performance of the cooling stave. The smaller the thermal resistance, the better the overall heat transfer performance is. The calculation method of the thermal resistance of the blast furnace stave is illustrated with a practical example. The influence of the radius of the water pipe, the water pipe interval and the shape of the water pipe on the maximum temperature and the thermal resistance of the cooling stave is discussed. The result shows that:

(1) Increasing the radius of the cooling water pipe or decreasing the interval of the cooling water pipe can both effectively improve the thermal safety and the overall heat transfer performance of the cooling stave. The comparative analysis shows that: with the same thermal resistance decline, reducing the cooling water pipe interval can reduce the maximum temperature of the hot surface more effectively, thus improving the thermal safety of the cooling stave; while with the same thermal maximum temperature drop, increase the radius of the cooling water pipe can reducing the thermal resistance more effective, thus improving the whole heat transfer performance of the cooling stave.

(2) Changing the shape of the cooling water pipe from circular to elliptical with the same surface area can increase the maximum temperature and thermal resistance of the cooling stave. It will reduce the thermal safety and the overall heat transfer performance of the cooling stave.

(3) The maximum temperature and thermal resistance of the cooling stave have different changing tendency with the influence of different factors. In the optimization design of the blast furnace stave, the two evaluation indexes should be considered at the same time. The design scheme with smaller thermal resistance can be chosen on the premise of ensuring thermal safety, so as to improve the overall heat transfer performance.

6. References
[1] Qian Z, Cheng H E and Wu L J 2006 Heat transfer analysis of cooling stave based on thermal state experiment *Research on Iron and Steel* **18**(5) 10–13
[2] Wu L J, Zhou W G, Su Y L, et al 2008 Heat transfer analysis of blast furnace stave *International Journal of Heat and Mass Transfer* 51(11–12) 2824–33

[3] Wu LJ, Gao X J and Wang S 2013 Global optimization of blast furnace cooling stave based on grey correlation analysis *Journal of Tongji University(Natural Science)* 41(12) 1885–88

[4] Guo G S, Zhang J L, Li F G, et al 2015 Research on structure optimization of cast iron cooling stave with elliptic water pipes *Energy for Metallurgical Industry* 34(4) 28–32

[5] Liu Q and Cheng S S 2016 Heat transfer and thermal deformation analyses of a copper stave used in the belly and lower shaft area of a blast furnace *International Journal of Thermal Sciences* 100 202–12

[6] Guo Z Y, Liang X G, Zhu H Y 2006 Entransy——a physical quantity to describe the heat transfer ability of an object *Progress in Natural Science* 16(10) 1288–96

[7] Han G Z, Guo Z Y 2006 Two different thermal optimization objective functions: dissipation of heat transport potential capacity and entropy production *Journal of Engineering Thermophysics* 27(5) 811–13

[8] Zhu H Y, Chen Z J and Guo Z Y 2007 Experimental study on the electro-thermal simulation of the principle of extremum entransy dissipation *Progress in Natural Science* 17(12) 1692–98.

[9] Liu X B, Guo Z Y and Meng J A 2008 Entransy analysis of thermal resistance in heat exchangers based on entransy dissipation *Progress in Natural Science* 18(10) 1186–90

[10] Qian X D and Li Z X 2011 Analysis of entransy dissipation in heat exchangers *International Journal of Thermal Sciences* 50(4) 608–14

[11] Feng H J, Chen LG, Xie Z H, et al 2014 Constructal entransy dissipation rate minimization for gas-turbine blade cooling *Journal of Mechanical Engineering* 50(4) 142–49

[12] Xu Y C, Chen Q and Guo Z Y 2015 Entransy dissipation-based constraint for optimization of heat exchanger networks in thermal systems *Energy* 86 696–708

[13] Guo J F and Huai X L 2016 The heat transfer mechanism study of three-tank latent heat storage system based on entransy theory *International Journal of Heat and Mass Transfer* 97 191–200

[14] Cheng X G, Meng J A, Guo Z Y 2005 Potential capacity dissipation minimization and entropy generation minimization in heat conduction optimization *Journal of Engineering Thermophysics* 26(6) 1034–1036

[15] Zhang Z M, Ren Z P and Mei F M 2007 *Heat Transfer* (Beijing: China Architecture and Building Press) 153–54

[16] Heinrich W G, Nikolas S and Wolffram G 1992 Die physikalischen verhältnisse im bereich der kohasiven zone des hochofens (teil 1: grundlagen und modelle) *Stahl und Eisen* 112(8) 73–79

**Acknowledgments**

This research subject is funded by the National Natural Science Foundation of China (51574179)