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Research Paper

Constructal designs for insulation layers of steel rolling reheating furnace wall with convective and radiative boundary conditions

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HIGHLIGHTS

- Constructal optimizations for multilayer insulation structures are performed.
- Minimum heat loss rate is taken as optimization objective.
- Two boundary conditions of the insulation layers are considered.
- One is convective heat transfer.
- Another is combined convective and radiative heat transfer.

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ABSTRACT

Constructal designs of multilayer insulation structures of a steel rolling reheating furnace wall are implemented by taking minimum heat loss rate (HLR) as optimization objective. Two boundary conditions of the insulation layers, convective heat transfer and combined convective and radiative heat transfer, are taken into account. The optimal constructs of the insulation layers with the two boundary conditions are obtained. The results show that for a multilayer insulation structure with convective heat transfer, the optimal thickness of each insulation layer is proportional to the square root of the temperature difference between the furnace wall and the ambient. For a multilayer insulation structure with combined heat transfer boundary condition, the optimal thicknesses of the multiple insulation layers increase with the dimensionless longitudinal coordinate. The HLR of the insulation layers with optimal thicknesses is reduced by 9.50% than that of the uniform ones, and this value decreases with the increase in dimensionless inlet wall temperature. Moreover, the nonuniformity of the convective heat transfer coefficient has an evident influence on the minimum HLR, but that of the surface emissivity is small.

1. Introduction

As energy crisis is becoming prominent, an effective way to make use of energy is what people chase for. Thermal insulation is an effective way to reduce the heat loss of a thermal system. Therefore, many scholars have shown great interests in the investigations of the thermal insulation problems, such as building enclosure structures [1–6], pipeline systems [7–11], etc.

Constructal theory [12–19] is a powerful theory for the optimal designs of various engineering applications, and many insulation problems [20–34] had been solved by using this theory. For the constructal designs of insulation layers of the reheating furnaces, Bejan [20] built the plane and cylindrical insulation layer models of a reheating furnace wall, and optimized the distributions of the layers with minimum heat loss rate (HLR). The results showed that the HLR of the insulation layer with optimal thickness was reduced by 12.5% as compared with that of the uniform one, and the heat loss reduction of the plane insulation layer with optimal thickness was larger than that of the cylindrical one. Kang et al. [21] built a multilayer insulation model of the furnace wall with constant temperature boundary condition, and carried out constructal optimizations of the insulation layers by taking minimum HLR as optimization objective. The results showed that the heat loss of the insulation layer with optimal distributed thicknesses was greatly reduced compared with that of the uniform ones, and the decrement of heat loss would be more obvious when the temperature distribution of the furnace wall was convex. Moreover, they also investigated the optimal distributions of the heaters in the reheating furnace with convective [22] and radiative [23] heat transfers by taking minimal fuel consumption as optimization objective. Based

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on the models in Refs. [20,21] and applied constructal theory [12–19] and entransy theory [24–29], Feng et al. [30–33] optimized the distributions of the single-layer insulation with constant temperature boundary condition and convective and radiative boundary condition, respectively. They concluded that the optimal distributions of the insulation layers were different from those obtained by HLR minimizations.

For the constructal designs of insulation layers of the hot fluid pipes, Bejan [20] built a distributed insulation layer model for a convective heat transfer hot fluid pipe, and optimized the thickness of the cylindrical insulation layer with minimum HLR. The result showed that optimal thickness of the insulation layer was uniform when the amount of the insulation material was fixed. Kalyon and Sahin [34] further discussed the problem in Ref. [20] by using optimal control theory, and the results obtained were coincided with those obtained in Ref. [20]. Moreover, they further optimized the distributions of the insulation layers of the hot fluid pipe with radiative as well as combined heat transfer boundary conditions [35,36], and obtained some different optimal distributions of the insulation layers. For the constructal designs of vertical insulating walls, Lorente and Bejan [37] optimized the internal structures of the vertical insulation wall subjected to a fixed mechanical stiffness and obtained the maximum thermal resistance of the wall. Furthermore, Xie et al. [38,39] and Chen et al. [40] reconsidered the insulation wall model in Ref. [37], and optimized the number of air cavities by considering heat flow, strength and wall weight simultaneously.

The constructal optimization of multilayer insulation structures with constant temperature boundary condition was carried out in Ref. [21]. Based on the multilayer insulation model in Ref. [21], a more actual model of multilayer insulation structures with radiative as well as combined convective and radiative heat transfer boundary conditions will be considered in this paper. Constructal optimizations of the insulation layers of a reheating furnace wall with the two boundary conditions will be carried out by taking minimum HLR as optimization objective. The optimal insulation performance with minimum HLR will be compared to that with average thicknesses of the insulation layers as well as that with minimum maximum temperature gradient. The model will be more generalized, and several heat transfer boundary conditions of the insulation layers will become special cases of this paper.

2. Constructal optimization of multilayer insulation structures

Consider a simple model of steel rolling reheating furnace wall with multilayer insulation structures, as shown in Fig. 1 [21]. The billet steel is heated by the high temperature gas in the inner of the hearth, and part of heat is dissipated to the ambient (ambient temperature T_0) through the furnace wall. The temperature $T(x)$ $(0 \le x \le L)$ of the internal furnace wall is specified. A number (N) of insulation layers (thermal conductivity k_i, thickness t_i, $i = 1, 2, 3, \ldots, N$) are laid outside of the furnace wall to reduce heat loss from the furnace. The length and width of the insulation layers are L and W, respectively. For the simplification of the calculation, the parameters along the third dimension (width direction) are assumed to be not varied. In this case, the heat conduction model in the paper becomes two dimensional, and the width of the insulation layer is fixed at unit width, i.e., $W = 1$. When the thicknesses $t_i\,(i = 1, 2, 3, \ldots, N)$ are much smaller than the length of the insulation layers, the heat transfer rate along the thickness direction is much larger than that along the length direction. In this case, the heat transfer along the length direction can be approximately ignored, and the heat conductions in the insulation layers can be simplified as one dimensional [21]. The models of the multilayer insulation structures with uniform and distributed thicknesses are shown in Fig. 1(a) and (b), respectively.

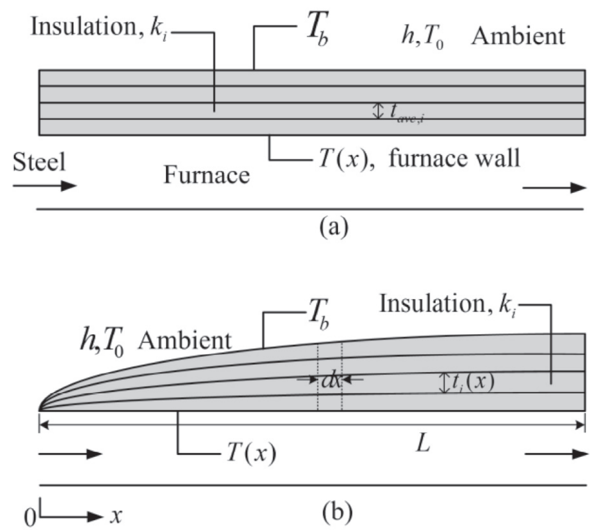

Fig. 1. Model of a reheating furnace wall with multilayer insulation structures [21]: (a) Insulation layers with uniform thicknesses (b) insulation layers with distributed thicknesses.

2.1. Convective heat transfer boundary condition

Consider the multilayer insulation structures with convective heat transfer. The convective heat transfer coefficient (HTC) between the outside insulation layer and ambient is h. To obtain the analytical solution of the optimization result, the HTC is simply viewed as a constant in this section [34]. For the specified total area $A_i\,(i = 1, 2, 3, \ldots, N)$ (i.e. the volume) of each insulation material, optimal distributions of the layer thicknesses can be searched to obtain a lower heat loss of the insulation layers.

The heat balance equation in the dx section of the insulation layers with distributed thicknesses as shown in Fig. 1(b) is

$$\frac{T(x) - T_b}{\sum_{i=1}^{N} t_i/k_i} \cdot dx = h(T_b - T_0) \cdot dx \tag{1}$$

where T_b is the layer's exterior surface temperature. From Eq. (1), the exterior surface temperature and total HLR [21] of the insulation layers can be, respectively, given by

$$T_b = \frac{T(x) + hT_0 \sum_{i=1}^{N} t_i/k_i}{1 + h\sum_{i=1}^{N} t_i/k_i} \tag{2}$$

$$q = \int_0^L \frac{T(x) - T_0}{1/h + \sum_{i=1}^{N} t_i/k_i} dx \tag{3}$$

where $T(x)$ is varied along the length direction of the insulation layers; therefore, T_b in Eq. (2) is not uniform.

The area constraint for each insulation material is

$$A_i = \int_0^L t_i dx \tag{4}$$

The minimum HLR of the multilayer insulation structure with the constraint of Eq. (4) can be derived by optimizing the thicknesses of the insulation layers. From Eqs. (2)–(4), the corresponding Lagrange function Φ can be defined as