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Analysis of thermal energy performance in continuous annealing furnace

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HIGHLIGHTS

- A model for assessment of energy efficiency in the annealing furnace is established.
- The simultaneous effects of line speed and heating power distribution are studied.
- To maximize energy efficiency, both heating power and strip velocity are investigated.
- Effects of geometrical and operational parameters on overall efficiency are evaluated.
- The pattern of heating power along the continuous annealing furnace is examined.

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ABSTRACT

In this paper, the effects of several parameters such as the strip width and thickness, strip velocity and also heating power produced by radiant tubes and its distribution on the overall efficiency of continuous annealing furnace were analyzed. A mathematical model was developed to compute the total heat absorbed by the strip. Then, the overall efficiency was calculated. It was recognized that the strip with lower thickness and width may reduce the thermal performance of continuous annealing line. According to this study, both of strip velocity and heating power should be carefully adjusted in each heating schedule. One of the greatest benefits of this work rather than other previous studies is that both strip velocity and heat power are simultaneously considered such that the operator can make a better sense of setting parameters among tangible choices for a predetermined schedule. The results showed despite more heat provided at the entry of the furnace, the effect of adjusting the heating power at the exit of furnace on overall efficiency was remarkably more.

1. Introduction

One of the greatest energy consuming industries is iron and steel production lines which accounts for more than 5% of the world's annual energy demand [1]. With regard to large use of fossil fuel consumption and its pollution concerns, many researches have been conducted into energy saving and emission reduction. An optimal use of energy resources and enhancing energy efficiency in steel industry would decrease these concerns in the world [2]. The need of galvanized steel strip as a basic material prepared in steel industry for many industries such as automotive industry rather than other steel products in view of its high tensile strength and resistance to corrosion has been remarkably raised. The main section of galvanizing line is the so-called heat treatment section (heating section) which plays a prominent role in enhancing the strip quality. It is difficult to closely identify this dynamic characteristic of strip during heat treatment due to its high velocity and heat flux density. Both aspects of reaching an appropriate temperature at the end of heat treatment and not allowing the strip to be overheated are crucial. These achievements may be done with precise investigations and establishing a good model for real time and control actions. These efforts promise not only a remarkable depletion in the running cost but significant savings in the initial cost investment and the space required.

In other words, in energy intensive industries, such as metal heating furnaces, response to energy saving, laborsaving and producing high quality products within less time are expressed to be a general concern which may cause that most scientists seek an improve in the energy efficiency of such furnaces. Based on that, we preciously have to have a good grasp of the problem and be able to exactly simulate the heating process in these furnaces.

It is crystal clear that overheating brings about heat loss in heating zones and a lot more for cooling the strip. Therefore, recognizing the major parameters for accurate prediction of the strip temperature can increase the efficiency of continuous annealing furnace. Many extensive

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Nomenclature

A	surface area, m^2
c_p	specific heat capacity, J/kg.K
E	Internal energy, J
F	configuration factor (shape factor)
h	specific enthalpy, J/kg
$\bar{h}$	average convective heat-transfer coefficient, $W/m^2 \cdot K$
J	radiosity at a surface, W/m^2
k	thermal conductivity, W/m·K
m	mass, kg
$\dot{m}_{HNX}$	mass flow rate, kg/s
M	total number of surface zones
q	heat flux, W/m^2
Q	heat transfer rate, W
t	thickness, m
T	absolute temperature, K
v	strip velocity, m/s
w	width, m
x, y, z	coordinates, m

Greek symbols

δ	Kronecker delta
ε	surface emissivity
η	efficiency
ρ	density, kg/m^3
σ	Stefane-Boltzmann constant, 5.67×10^8 $W/(m^2 K^4)$
τ	time, s
∂	differential
Δ	space discretization
$\sum$	summation
α_{Strip}	thermal diffusivity, m^2/s

Subscripts

i,j,k	indices for cell face, cell, zone, zone surface
$m1$	neighboring radiant tube, tunnel or strip element

Superscripts

Ref	refractory

researches conducted on studying the heat treatment in continuous annealing or reheating furnaces can be typically classified into three categories which are as follows.

1.1. Furnace structure

Some researchers have focused on details of furnace structure, its components and operational conditions in heat treatment. Belenkii et al. [3] have proposed several methods and different tools for real-time monitoring of the parameters of furnace components and conducted some tests on units which may help operator better understand the thermal performance in continuous furnaces and even improve the thermal efficiency. Most studies pertaining to furnace structure have been established to study the thermal behavior of radiant tubes. The effect of non-uniform heating flux on the performance of metallic and ceramic radiant tubes was considered in [4]. Its authors proved that a recirculating design can cause a uniformity in heat flux and lower NOx emission from radiant tube. Note that their design leads to high thermal efficiency and low cost. The use of preheat air recirculated for combustion can save the fuel consumption about 15–50% with respect to no heat recovery. A new design of low-NOx burner employed in a heavy forage furnace was introduced by Nishimura, et al. [5] which could save energy by 55%. In this article, the effect of inclined angle of fuel injection on thermal performance of this burner was investigated. Furthermore, the effect of rolls, applied for conducting the strip within the furnace, on the temperature field of the strip has been examined in [6–8]. With regard to contact heat transfer, such rolls influence the temperature distribution of strip. They showed that the strip temperature considerably increases after its contact with the rolls. In fact, a sudden clear temperature gradient may be observed after it passes through rolls which results in a non-uniform temperature distribution and consequently less strip quality. Skid marks for reheated slabs were also considered and some ways such as improvement to the shape and geometry of skids and applying the insulation to the supports have been proposed by Ward and Probert to be reduced their effect and heat losses [9]. Some studies have been conducted to search into different ways and operational conditions in which they can ameliorate the thermal performance. An experimental analysis of energy efficiency encompassing the operational conditions such as pertinent excess air coefficient, losses in recuperator, compensation of the air leakage and establishment of the economizer in rolling mill of a reheating furnace has been carried out that saved the energy and thereby, increasing the efficiency of reheating furnace [10]. It was reported that the energy may be saved by reducing the excess air, prevention of air leakage in the recuperator and utilizing of the flue gas heat. An analytical analysis of exergy and energy for both combustion and annealing chamber was developed to calculate the energy and exergy losses, energy saving, overall energy and exergy efficiency of the furnace [11,12]. Saboonchi et al. [13] proposed a new schedule for heat treatment in batch furnace which reduced the specific energy consumption. In addition, this plan could cause to shorter time for heat treatment and less hydrogen consumption. This numerical model used an experimental dataset for correction of inner wall and convector temperature. Despite the fact that in our work the strip temperature at the exit of furnace is controlled in order for it would have the desirable temperature for other purposes, their study only controlled the position where the coldest temperature happened. Therefore, there was no other controls of the coil temperature at final.

1.2. Thermal modeling

There exists a large number of thermal modeling of strip in the literature in which some empirical relations, CFD approaches and first-principle models were proposed. A compound model of 2D furnace body and 1D strip for optimization purposes in annealing furnace under both steady and transient conditions was developed in [14]. This model created with COMSOL Multiphysics software took into account the complex internal geometry of the furnace for simulation. As a matter of fact, due to lack of experimental data, this computer model was used to take measures of the furnace temperature for a simple model. This simplified model was provided based on energy balances for different furnace components to explore the efficacies of some parameters such as increased heating of the strip edges and cooling of thermocouple probes due to radiative exchange on thermal performance of the furnace [15]. A commercial finite element code has been employed by Chen et al. [16] for prediction of the temperature and stress distributions in continuous annealing lines. Su [17] carried out a steady-state CFD modeling to assess the flow, temperature and concentration field. The radiative heat flux and convection heat transfer coefficient along the furnace were calculated.

Most studies in this category employ energy balance methods for the temperature evaluation of the strip. A mathematical model consisting of radiant-tube and furnace-enclosure models based on energy balances and physical relations for a gas-fired radiant-tube continuous reheating