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Mathematical modeling of tube cooling in a continuous bed

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HIGHLIGHTS

- The study of heat treatment during the cooling tubes in an industry.
- Experimental data were collected.
- The cooling process is modeled by the FVM.

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ABSTRACT

The bar and profile manufacturing process in the steel industry utilizes controlled speed cooling in order to facilitate transformations in their shape as well as to bring about changes in the mechanical properties of steel. A computational algorithm is developed in this work that is able to reproduce thermal behavior of tubes as they pass through a cooling bed. This model takes into consideration axial, radial and angular temperature gradients of the tube, heat losses by radiation and forced convection in the first part of the bed and radiation and natural convection in the second part. Various radiation configuration factors and convective coefficients are utilized to represent the conditions of the problem. Results coming from resolution of the model by the employment of the Finite Volume Method were compared with data from literature and with results of experiments carried out in the thermal treatment hangar of the Vallourec & Mannesmann Tubes steel company located in Belo Horizonte, Brazil, which correlate well.

The mathematical model developed is utilized to determine the variation of the temperature profile in relation to radial, angular, and axial coordinates.

1. Introduction

The bar and profile manufacturing process in the steel industry utilizes heat to facilitate changes in shape as well as to alter the mechanical properties of steel. Heating followed by cooling seeks to meet the intended objectives. In manufacturing steel bars and profiles, for example, thermal treatment is an integral part of the manufacturing process, seeking to give steel the desired mechanical properties. Thermal tempering and recovering treatment are normally used in steel bar and profile manufacturing for use in cauldrons, rollers, in the automotive, petrochemical, naval, and aeronautical industries, among other applications.

Many industrial systems usually need to heat or cool products, for processing reasons. According to Hashmi [1], steel tube manufacturing methods can generally be divided into (a) seamless and (b) welded, in external diameters from several meters down to a few nanometers. Deng and Kiyoshima [2] and Yaghi et al. [3] presented numerical simulations of distributed residual tension in welded tubes. Reggio et al. [4] developed a computational analysis relating to the three-dimensional heat exchange process during seamless tube manufacturing employing computational fluid dynamics software based on the finite volume methodology. Park et al. [5] studied an indirect hot-stamping process consisting of forming at room temperature, heating, and water quenching in a tube. The heat convection coefficients used in the analysis were directly measured at various positions of the tube (e.g., outside, inside, and bending region) using thermocouples, and the final values were determined through correlation between the actual tests and numerical analysis. The experimental and simulated final deformed shape and temperature distribution were in good agreement. Gerardo et al. [6] developed a two-dimensional of induction heating of steel-tube end, that takes into account magnetic induction saturation and temperature dependence of material properties as an aid to process design and optimization. The model

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Nomenclature

A	area (m^2)
c	specific heat (J/kg K)
D_e	tube external diameter (m)
D_i	tube internal diameter (m)
$F_{i\text{-}\infty}$	ring form i-surroundings factor
Gr	Grashof number (adimensional)
h_c	convection coefficient (W/m^2 K)
h_r	radiation coefficient (W/m^2 K)
J	radiosity (W/m^2)
k	thermal conductivity (W/m K)
L	tube length (m)
L_c	characteristic length (m)
Nu_{Local}	local Nusselt number
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
q_c	convective heat flux rate (W/m^2)
q_r	radiative heat flux rate (W/m^2)
r	radial coordinate (m)
Re	Reynolds number
Ra	Rayleigh number
S	source expression
$\overline{S}$	source expression after integration with control volume
t	time (s)
T	temperature (°C)
w	tube angular velocity (rad/s)
z	axial coordinate (m)
ε	emissivity
θ	angular coordinate (rad)
ρ	specific mass (kg/m^3)
σ	Stefan–Boltzmann coefficient (W/m^2 K^4)

is solved by finite difference method, and is validated by comparison with thermocouple measurements at an industrial facility at which three tubes are heated concurrently prior to an upsetting process. Zhang et Al [7]. studied the deformation behavior of hot rolled steel pipe in compression in the temperature range of 1123–1373 K and the strain rate range of 0.001 s^{-1} to 5 s^{-1}. It is found that the flow stress behavior is described by the hyperbolic sine constitutive equation in which the average activation energy of 390 kJ/mol is calculated. And the hot deformation behavior of coiled tubing steel is characterized by using processing maps developed on the basis of the dynamic materials model.

Eismondt et al. [8] developed an automatic control system for the device used for reinforcement in thermoharden line of the rolling bar. The automatic control system allows monitoring and process control and the thermosetting equipment. A mathematical model was developed in C++ programming language and allows the simulation of the cooling process specified under any conditions. Angele et al. [9] studied the thermal mixing in the annular region between a top tube and a control-rod stem. The low frequency thermal fluctuations in this region can result in problems with thermal fatigue and have caused cracks in the control-rod stems of several nuclear reactors. The comparison between numerical and experimental results showed a rather good agreement, indicating that experiments with plant conditions are not necessary since, through the existing scaling laws and CFD calculations, the obtained results may be extrapolated to plant conditions. Pieve [10] presented a comparison between a theoretical model and the experimental data of the thermal performance of a jacketed pipe which belongs to an experimental facility aimed at testing the critical components of the externally fired combined cycle. A proper model is identified to calculate the fluid temperatures at the pipe exit, by considering a spatial discretization of the system, such that on each resulting section a differential equation is iteratively solved which gets as boundary conditions the output values arising from the preceding section. The comparison between expected and measured data was satisfactory according to the author.

Zhang et at [11]. presented a study the heat transfer phenomenon and the temperature field in the friction extrusion process. A friction extrusion experiment using aluminum alloy 6061 was designed and carried out, in which the mechanical power input during the experiment was recorded and the temperature variations with time at several key points surrounding the process chamber were measured using inserted thermal couples. A numerical thermal model for the experimental system was developed. Hansson and Jansson [12] studied a sensitivity analysis on a finite element model of glass-lubricated extrusion of stainless steel tubes. Fifteen model parameters, including ram speed, billet and tool temperatures, friction coefficients and heat transfer coefficients, were considered. The results show that the initial billet temperature is the factor that has the strongest impact on the extrusion force within the parameter ranges studied in the work. Lacarac et al. [13] studied the air-cooling of cylindrical bars in cross-flow and longitudinal flow. The air-cooling of steel specimens has been considered, from temperatures as high as 900 °C. It was observed that the cooling rate depends greatly on convective heat transfer coefficient. Two methods of assessing this parameter were compared; the use of proprietary CFD software, and an indirect measurement.

Load cooling (profiles, circular or rectangular bars, etc.) involves radiation and free or forced convection along the length of large beds. Load transport through the bed takes place due to its moving parts and in some stretches of the bed, the influence of gravity. Bed load velocity is responsible for controlling cooling speed.

There are various types of beds for different applications, the main types of which could be:

- Horizontal with a single cooling region, with a mechanical system, a gear-driven roll chain capable of turning the load, with or without fans below the bed rails;
- Horizontal with one or more cooling areas made up of fixed and mobile beams to move the load vertically and horizontally, with or without fans below the bed rails;

The most common situations found in steel companies in which there is bed-load movement are:

- The load (circular bar) moves along the bed at the same time as it is rotated around its own axis;
- The load is positioned on a sill walker made up of fixed and mobile beams. Load movement is this case takes place by means of movement of the beams.

Cylinders in cross flow have many engineering applications in cooling of electronic components, heat exchangers and cooling processes. Survey of the literature shows that, correlations for the overall averaged Nusselt numbers for forced convection heat transfer from circular and non-circular cylinders have been reported by different authors [14–17]. Sanitjai and Goldstein [14]