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Conference Paper · February 2018

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Modeling of Coil Cooling using 2D and 3D Computational Fluid Dynamics (CFD)

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1. Introduction – In metalworking, rolling is a metal forming process in which metal stock is passed through one or more pairs of rolls to reduce the thickness and to make the thickness uniform. The concept is similar to the rolling of dough. Rolling is classified according to the temperature of the metal rolled.

Image 1. Steel coil

If the temperature of the metal is above its recrystallization temperature, then the process is known as hot rolling. If the temperature of the metal is below its recrystallization temperature, the process is known as cold rolling. In terms of usage, hot rolling processes more tonnage than any other manufacturing process, and cold rolling processes the most tonnage out of all cold working processes.

Considerable researches have been devoted to research the thermal and microstructural behaviors of steels in controlled cooling process. For instance, Nobari and Serajzadeh [1] developed a mathematical model to predict temperature variations and austenite phase transformation in steel during controlled cooling. Shivpuri and co-workers [2] presented a computational approach to grain size evolution and mechanical properties of hot rolled rod. Yu et al. [3] developed an online Stelmor controlled cooling system for the stabilization of process operation. These numerical models have been successfully applied to controlled cooling process for realizing stable operation and improving product quality. Thus, in industrial practice, with more and more manipulated variables under control, the fact that the product quality varies with season and climate is more and more outstanding.

But up to now, it is no available in the literature to describe the quantitative analysis on the impacts of ambient temperature and humidity upon the cooling process of hot rolled steel. Fortunately, some investigations in the similar treatment were reported, Brenn. [4] Discussed the effects of ambient conditions on the drying process of liquid coatings on round metal wires. Page et al. [5] reported a model to analyze the effects of ambient conditions during air treatment operations of food. These research results provide base for the study of the effects of ambient conditions on the controlled cooling of hot-rolled wire rod of steel.

Steel Mills Lamination Coils Cooling, an integrated model for describing the effects of ambient conditions on the cooling performance of hot-rolled steel wire after rolling is presented. The effects of moist air on heat transfer have been derived from the theoretical and empirical models with the involved ambient conditions, and the results are used to calculate the temperature evolution and phase transformation of high-carbon steel, SWRH82B, by numerical approach. Then the predicted values of ultimate tensile strength are compared with the industrial trials to validate the model. Additionally, the inverse solution of wind speed is also discussed for realizing stable production process under different ambient conditions.

In hot-rolled steel production processes, controlled cooling after finishing rolling plays an important role on the final microstructure and mechanical properties of product. Steel coil produced at a steel mill after the laminate must be cooled from a temperature of 673.15 K to ambient temperature to be transported and sold. In this article a model to simulate and measure the rate of cooling coil is developed. The coil geometry employed is a cylinder with height between 1.6 m and 1.8 m and an outer diameter of 1.8 m. They have a few diameter co-axial hollow centre. The coils cooling take between 4 and 6 days depending on weather conditions. Usually the cold coil will be stored in a warehouse.

It produces unwanted stocks and thus represents a "bottleneck" in the marketing process. In this study, the process of coils cooling is studied using CFD techniques. To do so, 2D (two-dimensional) axisymmetric and 3D (three dimensional) transient models were used. The objective is to obtain the optimal rate of temperature decrease depending on the geometry and the orientation (horizontal or vertical arrangement) of the coils.

2. Material and methods – The geometry of the coils is cylindrical with an inner diameter of 0.18 m and outside diameter of 0.9 m and 1.8 m high. The coil is assumed to be located in a spacious room measuring 4.5 m x 4.5 m for 2D axisymmetric and 6 m x 6 m x 6 m for 3D model. Natural convection process for cooling was considered. In the present study, the geometry are performed using Gambit 2.4.6 Fluent Inc. USA and CFD package ANSYS FLUENT 16.0.0. for the simulations. To study vertical and horizontal coils cooling, 2D axisymmetric and 3D transient models were used respectively.

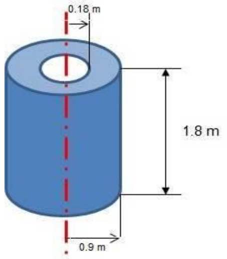

Image 2. Steel coil dimensions

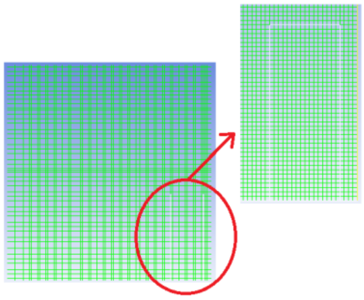

Image 3. 2D Axisymmetric models 10,000 cells

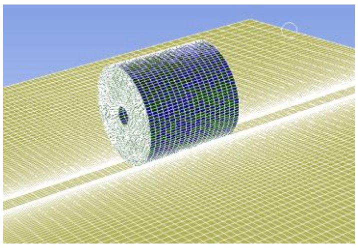

Image 4. 3D model 230826 cells

The 2D energy equation is as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\dot{q}=\rho C_p\frac{\partial T}{\partial t} \tag{1}$$

where T and t are temperature and time.

3D ANSYS FLUENT solves the energy equation in the following form:

$$\frac{\partial y}{\partial t}(\rho E)+\nabla.\left(\vec{v}(\rho E+p)\right)=\nabla\left(k_{eff}\nabla T-\sum_j h_j\vec{J}_j+(\bar{\bar{\tau}}_{eff}.\vec{v})\right)+S_h \tag{2}$$

Where k_{eff} is the effective conductivity ($k+k_t$ where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used), AND $\vec{J}_J$ is diffusion flux of species, *j*. The first three terms on the right hand-side represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. S_h Includes the heat of chemical reaction, and any other volumetric heat sources:

$$E=h\frac{p}{\rho}+\frac{v^2}{2} \tag{3}$$

Where sensible enthalpy *h* is defined for ideal gas as

$$\boldsymbol{h=\sum_j Y_j\,h_j} \tag{4}$$

And for incompressible flow as

$$\boldsymbol{h=\sum_j Y_j\,h_j+\frac{p}{\rho}} \tag{5}$$

Y_j is the mass fraction of species *j* and

$$h_j=\int_{T_{ref}}^{T}C_p.jdT \tag{6}$$

The value used for T_{ref} in the sensible enthalpy calculation depends on the solver and model in use.

For transport equations model we using the standard $k-\varepsilon$, the turbulence kinetic energy *k* and its rate of dissipation, ε are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{7}$$

$$\frac{\partial y}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}+(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{8}$$

Standard wall function, Momentum boundary condition based on launder-Spaulding law-of-the wall velocity yields:

$$U^* = \frac{1}{k}\ln(Ey^*) \tag{9}$$

where:

$$U^* \equiv \frac{U_p C_\mu^{1/4} K_P^{1/2}}{\tau_w/\rho} \tag{10}$$

$$y^* \equiv \frac{\rho C_\mu^{1/4} K_P^{1/2} y_P}{\mu} \tag{11}$$

The equation for radiation model (DO) is:

$$\nabla.(I(\vec{r},\vec{s})\,\vec{s}\,)+(a+\sigma_s)I(\vec{r},\vec{s})=an^2\frac{\sigma T^4}{\pi}+\frac{\sigma_s}{4\pi}\int_0^{4\pi}I\,(\vec{r},\vec{s}\,')\Phi(\vec{s},\vec{s}\,')d\Omega' \tag{12}$$

Natural cooling process is considered for both 2D axisymmetric and 3D models.
The selected Solver was pressure based, transient, and absolute.

a) Models use Energy equation, k-epsilon standard turbulence model, near-wall treatment and standard wall function.
b) Radiation model was DO (Discrete Ordinate)

Boundary conditions:

a) Bottom wall. It has been used calcium carbonate for assumption in the floor. Temperature 300 K.
b) Coils wall. Coupled was selected because thermal conditions were specified on the inner surface of the thin wall.
c) Left hand-side. The thermal condition that combines the convection and radiation boundary conditions by selecting the mixed option. With this thermal condition to set heat transfer coefficient, free stream temperature, external surface emissivity, and external radiation temperature is needed.
d) Upper. Set up radiation with specified external temperature.

3. Results and Discussion - To simulate the process, a transient simulations with different time steps were used. A sensitivity analysis demonstrated that the optimal time step is 800 s.
Table 1 and Image 5 show cooling coil mean temperature versus time comparison between 2D axisymmetric and 3D models. They are quite similar and almost identical from 3 to 5 days. Images 6 to 9 present the temperature and velocity maps for both models. They are coherent and show how the coils are cooling by natural convection and the most homogeneous temperature distribution corresponds to the horizontal arrangement of the coil (3D simulation).

Table 1. Cooling coils average temperature (K)

Days	2D Axisymmetric	3D
0	673.15	673.15
1/2	502.28	520.86
1	431.15	448.39
1.5	390.36	404.86
2	364.93	376.47
2.5	347.97	357.01
3	336.15	343.15
3.5	327.66	333.05
4	321.43	325.55
4.5	316.77	319.89
5	313.23	315.56

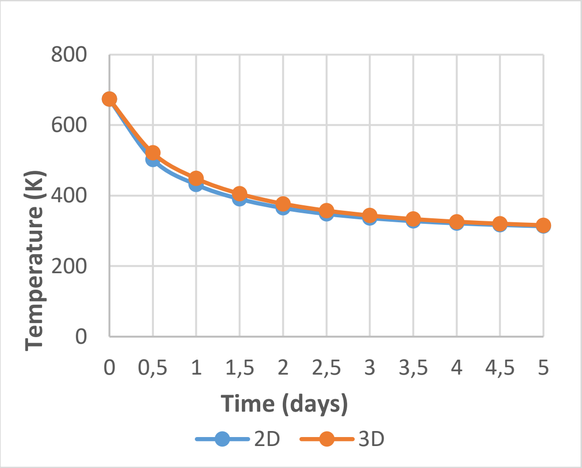

Image 5. Coil average temperature versus time

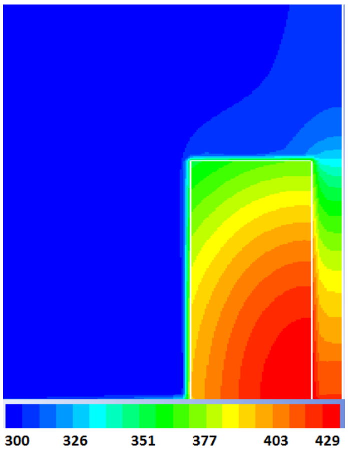

Image 6. Static temperature - 2D axisymmetric model

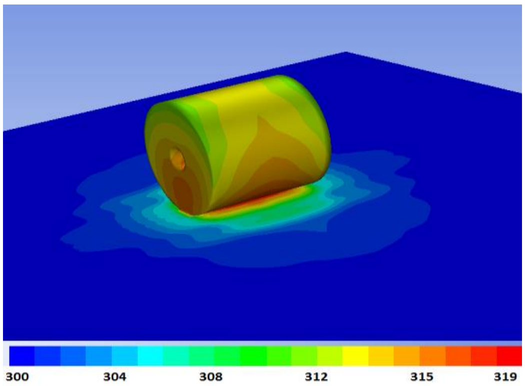

Image 7. Static temperature - 3D model

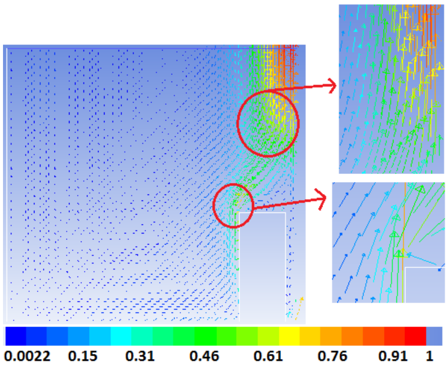

Image 8. Velocity vectors - 2D axisymmetric model

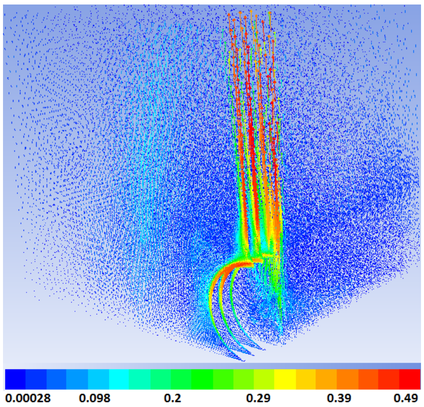

Image 9. Velocity vectors - 3D model

4. Conclusions - 2D axisymmetric and 3D simulation models have been used to study steel coils natural cooling. Both models are consistent and the results obtained are quite similar. It takes 5 days for a steel coil to be cooled from 673.15 K to ambient temperature; and relationship between average coils temperature and time is nearly equal. The most homogeneous temperature distribution corresponds to the horizontal arrangement of the coil.

In future works, cooling considering several rows of coils and optimal spatial arrangement will be studied, as well as the possibility of forced flow.

Acknowledgement

This work has been realized under Erasmus Mundus Swap and Transfer project, at the Department of Energy University of Oviedo, Spain.

5. References

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