Rotating Cylinders for Enhanced Heat Transfer in Annealing Processes

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A particular annealing process anneals steel coils at high temperature in a cycle of several days. This is a batch process in which steel coils are placed under an atmosphere cover over which an electrically heated furnace is used. Heating is performed in a hydrogen atmosphere to protect the steel. The use of fans has proven impractical historically due to high temperatures (>1200 ºC) that impact on blade components. By nature of the design of the process and lack of any convection, the steel and process equipment experience significant temperature differentials resulting in sub optimum properties of the steel and wear/failure of equipment. Thus, this project aims to investigate engineering options and challenges to introduce gas circulation into the gap between the heating element and the protective cover by means of exchanging some of the radiant heat transfer to convective heat transfer. This will reduce temperature differentials (hot spots) within the furnace space that can increase equipment failure rates and produce heating inefficiencies. Finite volume numerical simulation using ANSYS Fluent has been carried out to examine the effect of one possible solution through the use of rotating cylinders inside the furnaces. The rotating cylinder technique was used to generate recirculation and turbulence inside the furnace cavity, thus improving convection and heat transfer through the entire system. Results demonstrate that fluctuations resulting from the cylinder rotation improve mixing of the fluid and enhance energy transfer to their maximum with a vertical configuration.

1. Introduction

Excess capacity, over-production and energy expenses have been a constant concern in the steel industry for many years. Although the steel industry has managed to reduce its energy demand by nearly 60% in the last 50 years (World Steel association, 2014), increasing demand for steel is conflicting with factors such as profitability and environmental concerns (World Steel Association, 2015). Steel that is used in transformers is treated thermally through a process of heating and cooling in prescribed temperature and atmospheric cycles in order to obtain steels with appropriate mechanical and magnetic properties, thus requiring complex processes difficult to replicate. This treatment process is known as the annealing process.

The annealing process is a special heat treatment to release residual stresses from steel strips which occur because of reduced thickness after cold rolling. Steel strip coils are heated in a hydrogen atmosphere at a certain temperature in order to achieve recrystallization. Further details about the process can be found in various sources (Moon and Hrymak, 1999; Saboonchi et al, 2009; McGuinness et al, 2008).

At Orb COGENT Electrical Steels, part of the TATA Steel group, the annealing process is performed in electrical multi-stack annealing furnaces during approximately three days. The process starts by stacking steel coils and separator plates onto an empty base. A protective cover is placed over the stacks and settled in a sand seal in order to enclose the circulating protective atmosphere that prevents oxidation and participates in the heat transfer process. Figure 1 shows a schematic drawing of the furnace with the steel coils and inner covers. Due to the long operation conditions and lack of fluid circulation various issues result; the formation of hot spots and temperature differentials in areas of higher exposure ratio to the heating elements than the less direct areas; deformation of covers; energy increment and over-expenses; etc. Using standard circulation devices such as fans would require prohibitively expensive material to cope with the high annealing temperatures as well as the engineering work for their installation.

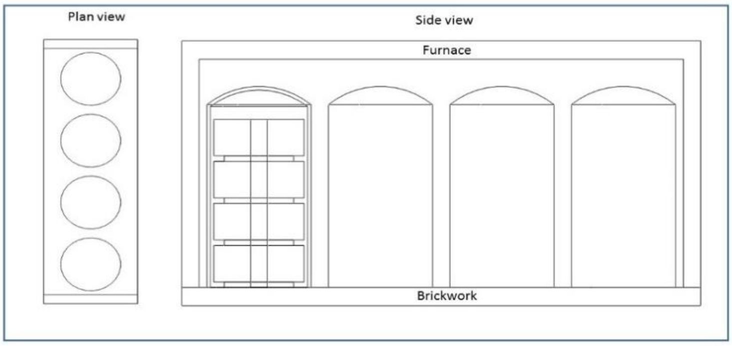


Figure 1 Plan and side view of the multi-stacks annealing furnace

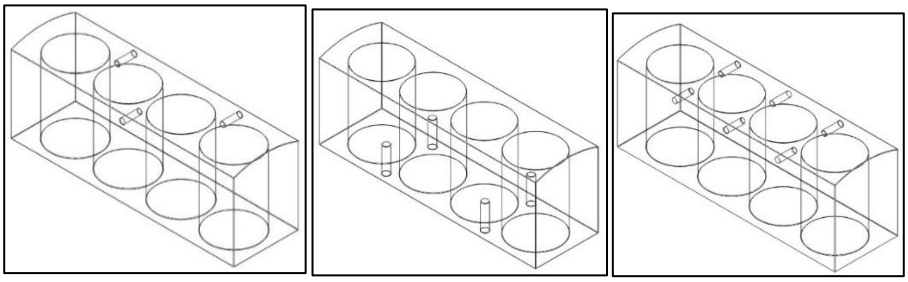
Therefore, the present study was devoted to investigate the usage of another form of mechanical device capable of improving convection to reduce hot spots, thus decreasing deformation and minimizing energy consumption.

1.1 Proposed technique

The technique of rotating cylinders with and without cross flow has received great deal of attention by scientists and researchers owing to its importance in a variety of engineering applications such as rotating heat exchangers, condensers for seawater distillation and dying of paper on rollers. Numerous researchers have investigated the effect of stationary and rotating cylinder on cross flow behaviour, numerically and experimentally (Ingham and Tang, 1990; Stojkovic et al, 2002; Martin-Alcantara et al, 2015; Park and Lee, 2000; Lang et al, 1998; Badr et al, 1988; Dennis and Chang, 1970). The majority of these published studies have focused on the effect of the rotation on suppressing vortex shedding activity behind bluff bodies. Results provide a better understanding of vortex shedding phenomenon and vortex interaction in downstream flows.

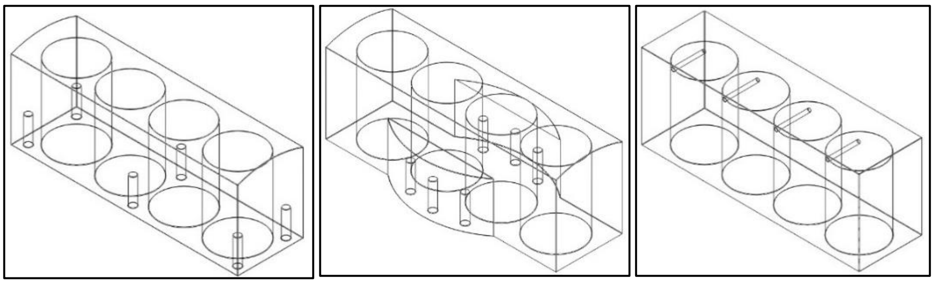
Various research groups (Mittal, 2003; Kumar, 2011; Paramane and Sharma, 2009; Paramane and Sharma ,2010) investigated the effect of rotating cylinders on flow behaviour with the emphasize on the flow pattern behind the cylinder. All studies concluded that rotation had the great effect of suppressing turbulence behind the cylinder. Elghnam (2014) and Dierich (1998) investigated a rotating cylinder in a quiescent fluid. Both stated the turbulent flow nature around the cylinder due to its rotational effects. Thus, foregoing published studies have confirmed the capability of rotating cylinders on customising fluid structures around them. This makes them potential engineering alternatives in applications where using other recirculation devices, such as fans, holds undesired consequences.

In the current study, rotating cylinders are explored as an option in order to generate recirculation inside COGENT's annealing furnace. The rationale behind the proposed concept is that during cylinder rotation there is a continuous layer of fluid thrown off from the surface in an irregular manner, owing to the centrifugal force. This layer is replaced by new a layer drawn inwards. Continuous growth of the fluid around the cylinder and within the fluid domain generates eddies and in turn recirculation, which are the main mechanisms of turbulence. Due to the furnace big size, more than one cylinder would be used in order to cover as much space as possible. Six different layouts with cylinders of various diameters and lengths located vertically and horizontally inside the furnace were suggested, Figures 2a and 2b.



Layout 1 Layout 2 Layout 3

Figure 2a: Schematic diagrams demonstrate the suggested layouts and the cylinder distribution inside the furnace.



Layout 4 Layout 5 Layout 6

Figure 2b: Schematic diagrams demonstrate the suggested layouts and the cylinder distribution inside the furnace.

All arrangements were investigated numerically in order to select the optimal design that can enhance flow convection, thus heat transfer distribution.

2. Numerical setup

The simulation focused on modelling the fluid domain inside the furnace cavity. The hydrogen atmosphere that occupies the gap between the heating elements and the inner covers was the target of the CFD work, internal features including the inner covers and the cylinders were introduced as boundary conditions to the fluid domain. The mesh was created using ANSYS mesh generator. A structured hexagonal grid mesh was created as it gives accurate results and drives the solution to converge more quickly. Figure 3 shows the grid of the fluid-domain for layout 4. A great deal of attention was given to the mesh quality in order to capture all the changes in the fluid structure. The number of elements varied in the six different layouts due to latter features, ranging from 380310 to 492767 elements. However, element size was kept the same for all the cases. Mesh quality was tested using ANSYS criteria such as the skewness and the orthogonal quality.

The simulation only considered the soaking cycle of the annealing process since it is the longest part of the cycle, i.e. more than 1 day. Additionally, at this crucial stage, the furnace reaches the maximum and fixed annealing temperature (not disclosed due to industrial secrecy). This allowed a numerical study focused on the fluid behaviour rather than on the temperature variations with time.

Cylinders with diameters of 100, 150 and 200 mm and lengths of 550 and 800 mm were examined. The rotational speed was set at 100, 150 and 200 rad/s for all the suggested layouts. All calculations were performed using ANSYS Fluent. Reynolds stress model (RSM) was used for turbulence modelling. The second order upwind scheme was used to discretize both momentum and energy equations, while the first order upwind scheme was used to discretize turbulent kinetic energy, turbulent dissipation rate and Reynolds stresses. SIMPLE algorithm was utilised for pressure-velocity coupling. Constant wall temperature boundary conditions were applied for the furnace and the inner covers walls.

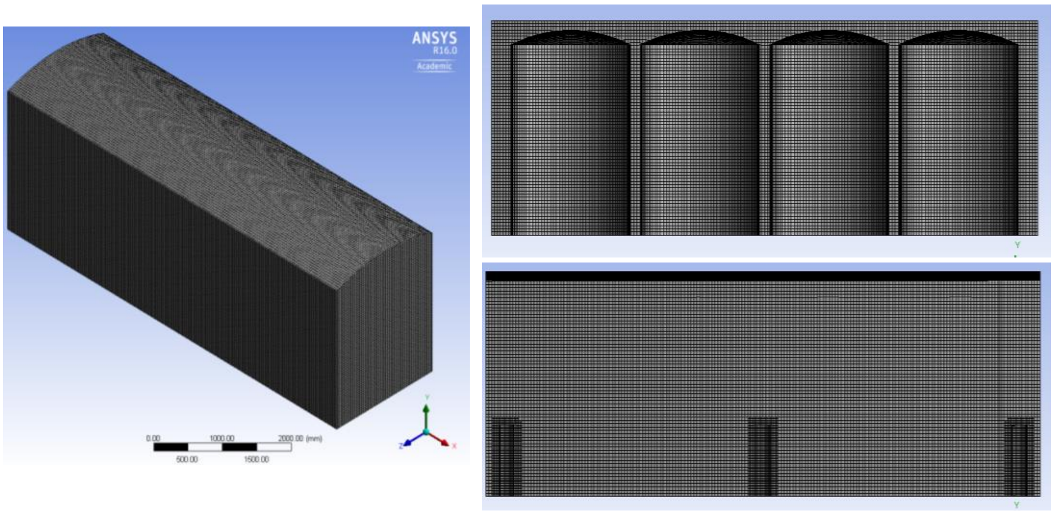


Figure 3: Mesh generation at layout 4

3. Results and discussion

Results were obtained for a number of locations across the geometry. Figure 4 shows plane locations in the absence of the cylinders. The distance between every two planes is the same for all the layouts in order to achieve appropriate comparison.

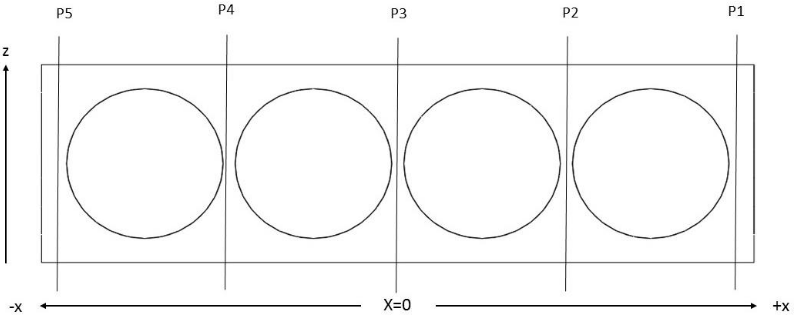
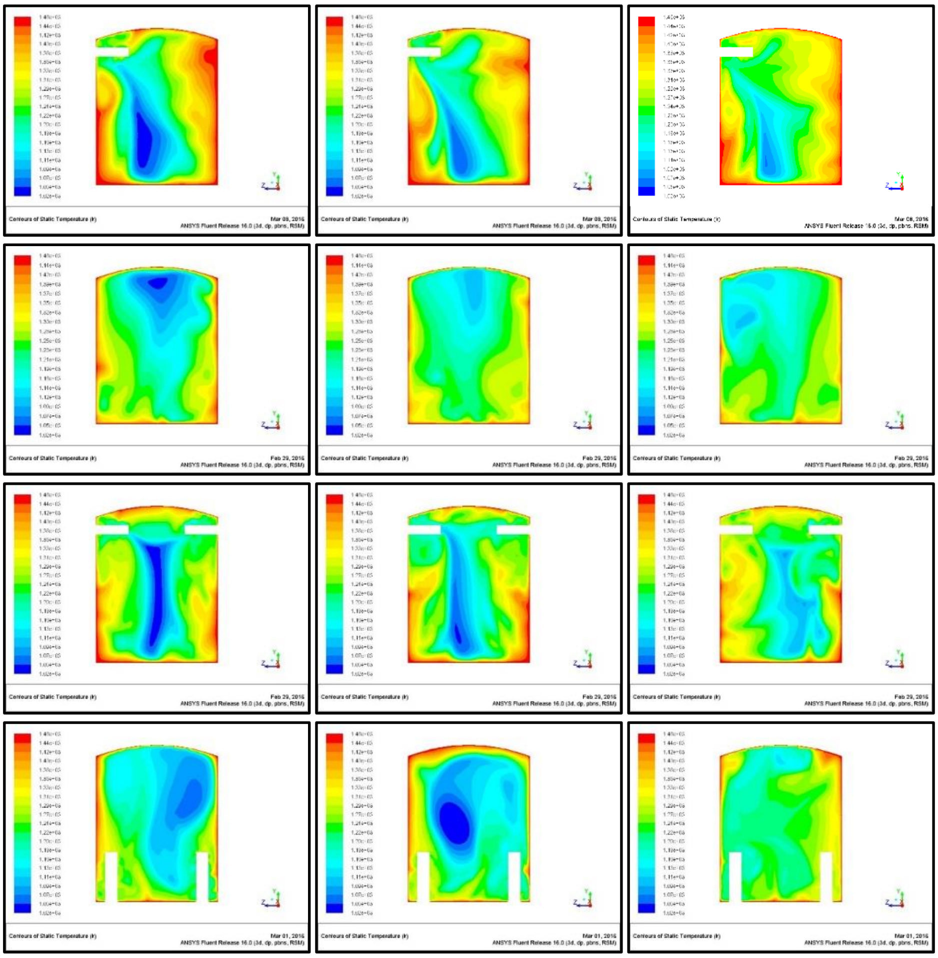


Figure 4: lines and plane locations in the absence of the cylinder

3.1 Temperature contours

Temperature contours in layouts 1, 2, 3, 4, 5 and 6 show that heat is going towards the cylinder under the influence of vortex formation, Figure 5. This is because heat transfer convection and fluid mechanics are strongly connected. Moreover, temperature contours show that for a particular layout temperature differentials decrease with increasing the rotational speed. However, vortex formation in layout 6 is confined between the top wall of the furnace and the top of the inner cover due to the location of the cylinders. Consequently, rotation had a poor effect on the fluid structure in this layout.



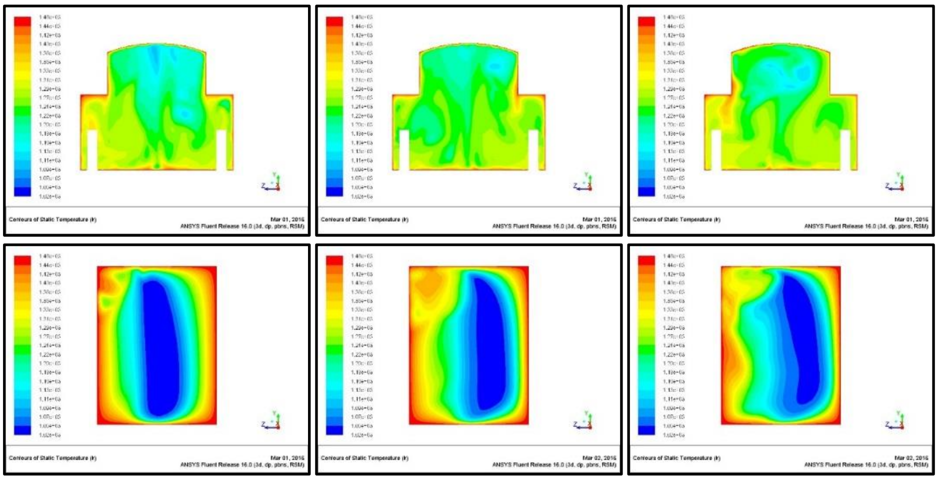
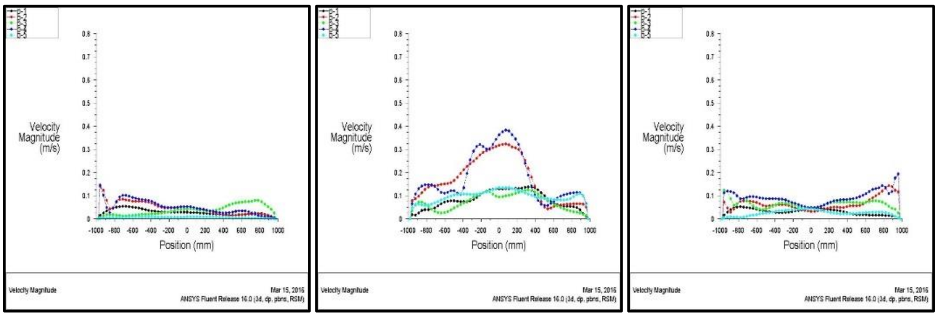


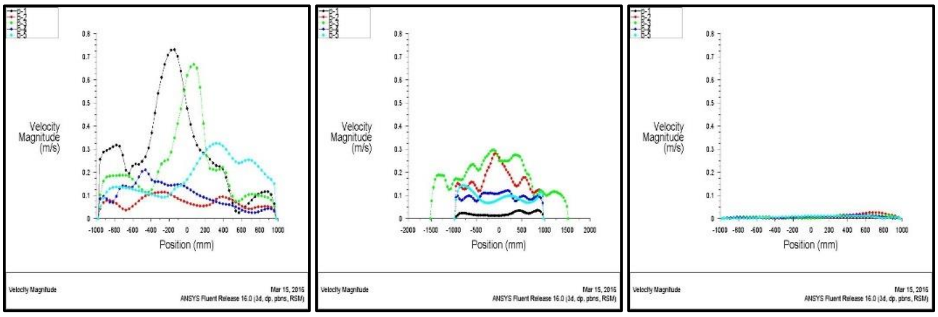
Figure 5: Temperature contours for the six different layouts at 100, 150 and 200 rad/sec, respectively. Plane 3.

3.2 Velocity profiles

Figure 6 shows velocity profiles for the six layouts at a rotational speed of 100 rad/sec. Velocity charts show fluctuations in velocity magnitude at five different locations across the geometry. This is due to the continuous growth of the fluid around the cylinder. This generates eddies at various scales within the fluid domain, thus turbulence that enhances convection.



Layout 1 Layout 2 Layout 3



Layout 4 Layout 5 Layout 6

Figure 6: Velocity charts at a rotational speed 100 rad/sec.

The resultant velocity increases with increasing the rotational speeds due to higher tangential velocity. However, as previously stated, the velocity in layout six records the minimal values in comparison with the other five cases. It was noticed that for those layouts where the cylinders are located vertically the velocity is higher than for the cases where the cylinders are installed horizontally. This is mainly caused by the location of the cylinders and their relative position to the walls and inner covers, which act as velocity dampers. Density fluctuations across the profile also affect this phenomenon, with lower density at the top of the confinement, hence less fluid mass movement around the cylinders. Due to the adapted feature in layout 5 and cylinders location, the recirculation was poor near the walls when using those profiles. Therefore, layout 4 seems to be the best in terms of convection improvement, although layout 2 has a friendlier technical implementation.

4. Conclusions

The present work numerically investigated the use of rotating cylinders to introduce gas recirculation inside high temperature coil annealing furnaces. Six different cylinder arrangements were suggested. Results showed:

1. Fluctuations in velocity profiles and eddies formation near the walls and the cylinders is due to cylinder rotation and vortex formation.
2. The temperature differentials decrease with increasing rotational speed.
3. The velocity fluctuations increase with increasing the rotational velocity.
4. The greatest improvement was observed in vertical configurations, with particular emphasis on layout 4 that has rotating cylinders in the corners, a technical challenge for implementation purposes.

The next step of this project is to test the best layout, from practical standpoints, using transient solution. Then built a prototype to test the validity of the concept of rotation.

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