Development of Convection in High Temperature Coil Annealing Furnaces Using Rotating Cylinder Technique

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Abstract

The present study investigates the usage of rotating cylinders to generate gas circulation inside high-temperature coil annealing furnaces during the annealing treatment of grain-oriented electrical steel. This technique has been investigated to reduce temperature differentials (hotspots) within the furnace space, a phenomenon that occurs due to extremely high temperatures, the static nature of the gas inside of the furnace and long operation conditions. Finite volume numerical simulation using ANSYS Fluent was performed to test the validity of the proposed technique. The numerical results showed fluctuations in velocity magnitude of the fluid in comparison with a case when the technique was not employed. This is because of the vortex generation under the effect of the cylinder rotation. The generation of turbulence enhances gas-mixing quality, and thus it would save a great amount of energy required for the process, producing a product with desired magnetic properties at lower cost.
Keywords: Rotating cylinder technique, Annealing furnace, Convection enhancement, CFD

1. Introduction

In the steel industry, grain oriented GO electrical steel is a speciality steel tailored to produce excellent magnetic properties including high permeability and low energy loss when magnetised under AC conditions in devices such as transformers, reactor and inductor cores [1]. The main metallurgical feature is the abnormal grain growth texture developed by secondary recrystallization during the high-temperature coil annealing (HTCA) process [2].
The production of GO steel is highly complicated and requires a careful multi-step to achieve steel with favourable magnetic properties. In general, GO steel production starts from conventional steelmaking, then follows continuous casting, slab reheating at 1,400˚C, hot rolling to 2-3 mm, annealing of the hot-rolled sheet for a short period and a two-step cold rolling with intermediate annealing or a single cold rolling with large sheet thickness reduction. The last stage of the process starts with a primary annealing re-crystallization in a wet hydrogen atmosphere for decarburizing purposes. The superior grain structure develops during the HTCA where the secondary recrystallization occurs [3] in a dry hydrogen atmosphere.
During the HTCA process, the steel coils are first heated up slowly using a gas mixture of hydrogen and nitrogen (heating up stage). Then the charge is held in a 100% hydrogen atmosphere at high temperature for several hours (soaking). Finally, cooling is carried out in an atmospheric gas of NHx mixtures; the whole HTCA process (i.e. heating-up, soaking and cooling) lasts up to one week [4].
At Cogent Power Orb Electrical Steels, part of the TATA Steel group, the HTCA process is performed in electrical multi-stack annealing furnaces. The process starts by stacking steel coils and separator plates onto an empty base. Protective covers are placed over the stacks and settled in a sand seal, which helps in enclosing the circulating of the protective atmosphere. A furnace bell is then lowered on the base. Then a flow of deoxidizing gas starts to purge the air from the space under the inner covers and the furnace bell. Fig.1 shows a schematic diagram of the furnace with the steel coils charge and inner covers. The furnace bell is equipped with four zones of heating elements attached to the side walls, Fig.1, which deliver heat to the charge via radiation and some convection.

Due to space limitations and long operation conditions as well as the extreme high annealing temperature (~1,200˚C), some issues result such as the formation of hotspots. Hotspots can occur in the event of electrical failure (i.e. open circuit) in one of the heating elements. Thus, the remaining zones will need to work harder to try to deliver the requested thermal cycle. Because of the lack of fluid recirculation, to re-distribute the excess heat away, the areas close to the active heating elements receive a great amount of energy by radiation and become hotter than those near to the inactive heating zone that is relying only on some convection induced by buoyancy forces from the vicinity areas. The situation gives rise to forming the hotspots and further issues.

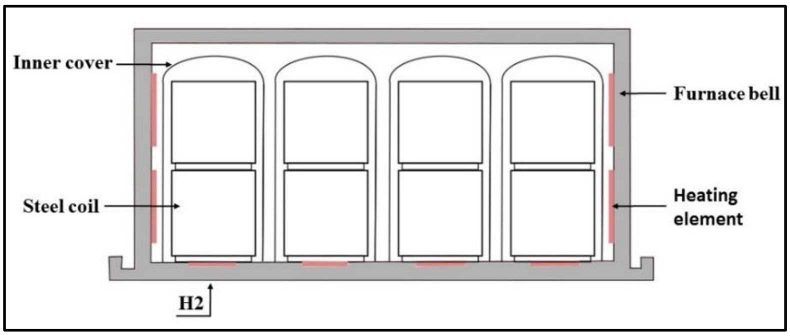


Fig.1. A schematic drawing of HTCA annealing furnace.

The issue escalates as the process duration becomes longer. Zone with a deficit of heat or hotspots leads the steel coils to experience high temperature gradients, thus not receiving the correct heat treatment for a long time, which affects, dramatically, the quality of the final product and the cycle time. Other issues associated with the thermal inefficiency that is represented by the formation of the hotspots, are the deformation of inner covers and the increase in energy consumption to accomplish the annealing requirement.
To overcome the thermal inefficiency (hotspot) issues, gas recirculation needs to be introduced during the annealing process to enhance gas mixing quality and to redistribute heat inside the furnace cavity. A recirculating gas flow can produce almost uniform temperatures on the surface of the charge and other process equipment. Gas mixing is obtained by generating turbulence within the fluid domain via using an agitator device. Using (super-alloy) fan to cope with the high annealing temperature has always been prohibitively expensive not to mention the engineering work required to convert a base to be able to power and seal the fan perfectly, bearing in mind that the (HTCAs) furnaces operate using a hydrogen atmosphere. Therefore, the present study was devoted to investigating the usage of another form of mechanical device capable of producing fluid circulation within the fluid domain inside furnace cavities, thus enhancing convection to reduce hotspots and minimising energy consumption.

1.1 Proposed technique

A great deal of attention was given to the rotating cylinder technique, owing to its importance in a variety of engineering applications such as rotating heat exchangers and reactors for seawater distillation [5]. Flow around a rotating circular cylinder has been investigated widely, because of its simple geometry, which facilitates understanding the wake dynamics [6], and the phenomena associated with the interaction of a fluid with a moving solid surface. For instance, the mechanisms of the near wake formation and the development of the von Karman vortex street behind a rotating cylinder were analysed by Bader et al. [7] and Ingham et al. [8]. The vortex generation concept associated with similar mechanical devices and its role in improving mixing quality and energy transfer was the driven force for investigating the rotating cylinder technique [9]. Results provided a better understanding of vortex shedding phenomena and vortex interaction in downstream flows [10]. The capability of the technique on controlling the flow structure behind them was addressed in many other investigations. Stojkovic et al. [11] showed that cylinder rotation in cross flows influences significantly the flow pattern around the cylinder. In the case of cross flow bluff bodies, the phenomenon of vortex generation is governed by two main parameters namely Reynolds number and rotational rate. A study by Kumar et al. [12] found that vortices are suppressed at larger rotational speeds at the same Re number. Lang et al. [13] reveal in their numerical investigation of a two-dimensional flow around a stationary cylinder that vortex-shedding activity starts at a critical Reynolds number of 45.9. The vortex shedding activity is characterised by the turbulent flow occur in the downstream flow. Park et al. [14] and Chen et al. [15] experimentally examined the turbulent flow parameters in the wake region such as the turbulence intensity. They defined the vortex formation region as a region that has the maximum amount of velocity fluctuations.

A rotating cylinder in a quiescent fluid domain was addressed by Dierich [16]. The study states the turbulence flow nature around the cylinder due to its rotation. Most recently, the rotating cylinder technique was investigated by Escamilla-Ruiz et al. [17], as a fluid agitator in steering tank. Their findings revealed the formation of recirculation loops induced by inertial forces produced by the agitator. Thus, preceding published studies have confirmed the capability of the rotating cylinders on controlling fluid structures around them. However, the technique has only been a scientific curiosity rather than a real application, especially in high temperature processing applications. Therefore, in the current study, rotating cylinders are explored as an option to generate gas recirculation inside Cogent's annealing furnaces. 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, which is then replaced by a new layer drawn inwards. The continuous growth of the fluid around the cylinder and within the fluid domain generates eddies, which are the main mechanisms of the turbulence, and in turn recirculation.

Due to the big furnace size, more than one cylinder at high rotational rates would be used to ensure the propagation of the turbulence to a large domain inside the furnace. Six different layouts with cylinders of various diameters and lengths installed vertically and horizontally inside the furnace were suggested, Fig. 2.

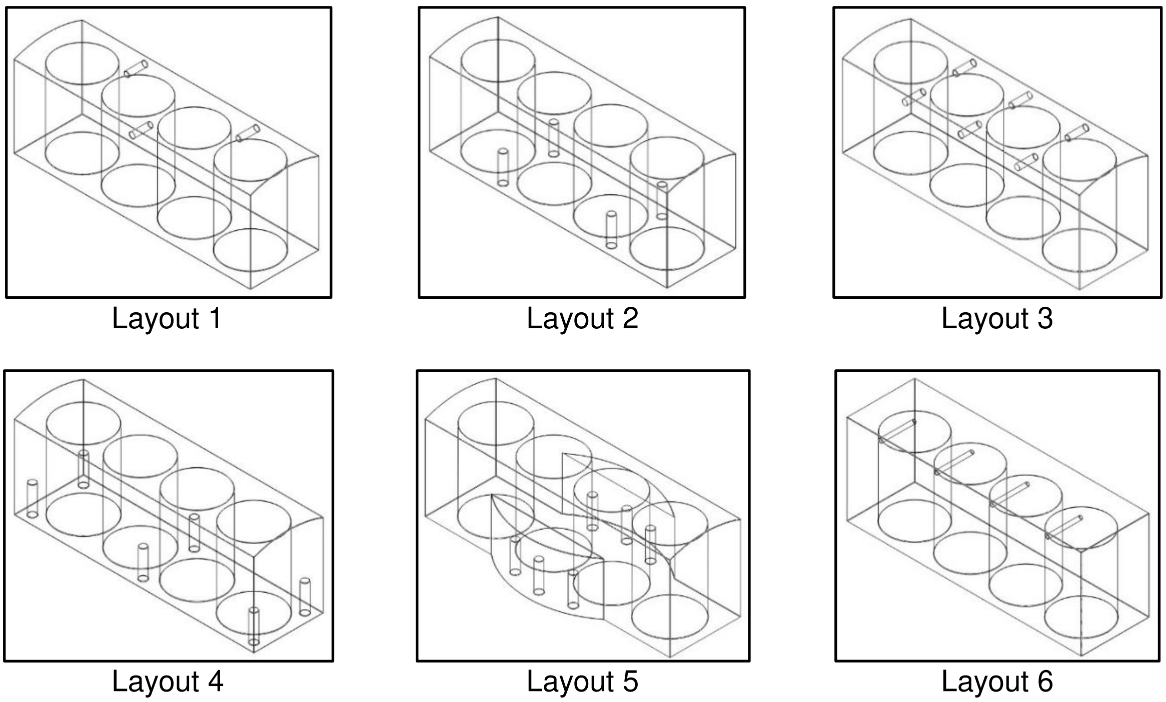


Fig.2. Schematic diagrams of the cylinder arrangements.

The internal furnace size, the process equipment layout and the limited space available were all considered when selecting the cylinders geometry and location. All arrangements were investigated numerically to select the optimal design that can enhance flow mixing, thus heat transfer distribution. Simple modifications on furnace geometry were made in layout 5 and 6 to fit the cylinders on their selected positions.

To obtain a qualitative and quantitative assessment of any alternative technique, an energy analysis will be conducted on several annealing furnaces at Cogent Power Orb Works. The energy benchmarking study would also help in identifying possibilities of energy saving by minimising energy losses and improving energy usage through the system. The study will be focusing on the energy losses during the full annealing process of the grain oriented material. Using some available data collected from the HTCA's operating records at Cogent Power, a preliminary analysis of energy performance of a HTCA furnace, as it stands now, was performed and an estimation of the energy losses is described in Sankey diagram shown in Fig.3. It illustrates the energy enters the furnace, energy that is mainly derived from electrical power inputs of about (~95%). The furnace bell is tailored to minimise heat losses through the furnace walls. However, during the annealing process, an amount of the heat supplied is wasted via radiation from the furnace wall to the surroundings, which is characterised by the shell loss (~8%). Another energy loss occurs through the cooling medium (~28%) and the reheat of the inert gases (~15%). The remaining energy portion is exchanged to achieve chemical changes for secondary recrystallization, purification and glass film formation within the steel coils.

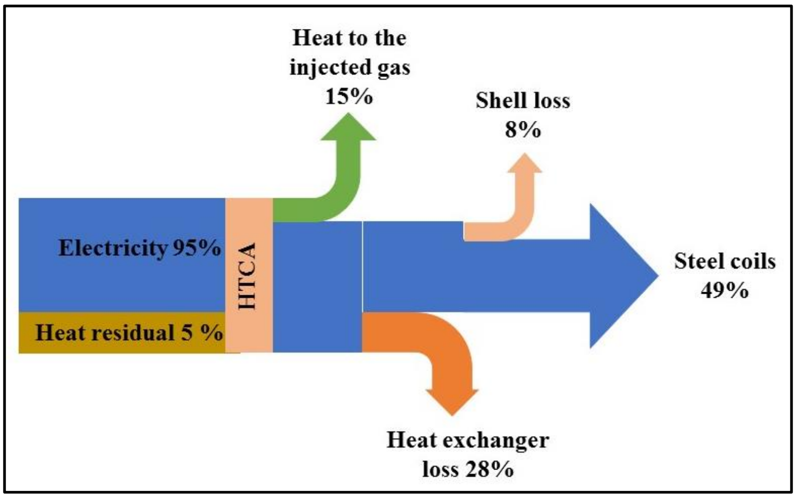


Fig.3. Sankey diagram for HTCA furnace.

2. Calibration

Prior to the current study, an experimental and numerical investigation of a flow passing a rotating cylinder was performed [18], Reynolds Stress Model (RSM) was used in the numerical approach, and showed good performance when applying it in modelling of rotating bodies. It also showed good agreement with previously published studies such as Paramane et al. [19]. Since the turbulent model was calibrated in previous work with cases of rotating bodies, it was used in the present study to test the validity of the proposed technique. A model such as Reynolds Stress Model (RSM) describes the solution that comprises the behaviour of eddies in a time-averaged fashion. In this approach, the solution passes through a statistical filtering procedure that aims at omitting the small-scale fluctuations and describes the average state of the flow. Moreover, Reynolds stress model has shown superior predictive performance in rotating fluids and buoyant flow [20]. Therefore, this model was determined as the best to capture the changes in fluid structure resulting from cylinder rotation.

3. Numerical setup

The simulation was designed to test the validity of the rotating cylinder technique inside high temperature coil annealing furnaces during operating conditions. It was focused on modelling the fluid domain inside the furnace cavity. The 100% H_2 atmospheric gas that occupies the gap between the heating elements and the inner covers was the target of the CFD work. Thus internal features including the inner covers and the cylinders were introduced as boundary conditions to the fluid domain. The CFD modelling considered the soaking cycle of the annealing process because this process has the longest duration usually takes approximately one 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.

The mesh was created using ANSYS mesh generator. A structured hexagonal grid was created as it gives accurate results and drives the solution to converge more quickly.

Fig.3 shows the grid of the fluid-domain for layout 4. A great deal of attention was given to the mesh quality to capture all the changes in the fluid structure. Three meshes were examined to perform a mesh independence analysis, Table 1. After carrying out the analyses, it was decided to use a medium size mesh that consists of ~773,780 nodes and 773,780 elements and that provided mesh-independent results when compared to the high size mesh. The mesh was created with structured grid creating a higher node density near the cylinders. Elements size was kept the same for all layouts. For further checking, mesh quality was also tested using ANSYS criteria such as skewness and orthogonal quality. The hexagonal elements with orthogonal of 0.99 were found very good to achieve a converged solution.

Table 2

Various mesh densities for independence analysis

Mesh density	Number of elements
High	870,004
Medium	773,780
Low	431,223

Cylinders with diameters of 100, 150 and 200 mm and lengths of 550 and 800 mm were examined. The cylinders with small diameter (100 & 150) were used in the horizontal arrangements to fit in narrow spaces inside the furnace, while the bigger cylinders of dimensions 200 in diameter and 800 height were used in vertical arrangements.

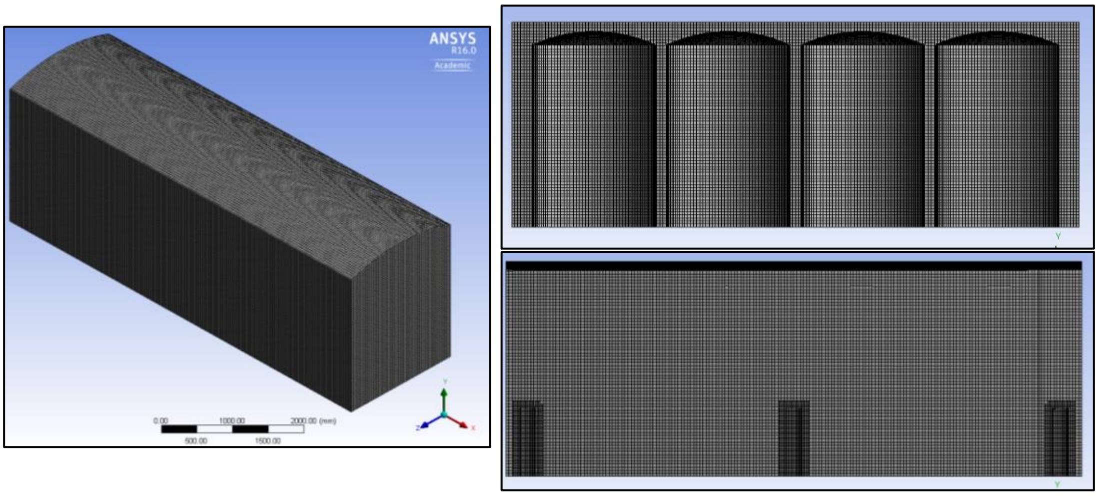


Fig.4. Mesh generation for layout 4

The velocity of fluid leaving the cylinder surface must be high enough to distribute the gas into the most remote parts of the furnace to obtain mixing. Therefore, 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. SIMPLE algorithm was utilised to couple velocity and pressure terms. Constant wall temperature boundary condition was applied to the furnace and the inner covers walls. The thermal and physical properties of the H_2 are varied through the furnace due to the variation in temperature. To facilitate the numerical modelling the properties were assumed as constant and were taken from the literature [21], and no reactions were assumed [22]. The flow is governed by the unsteady Navier-Stokes equations for an incompressible viscous flow, which expressed in the following form for continuity and momentum.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial (uu)}{\partial x}+\frac{\partial (vu)}{\partial y}+\frac{\partial (wu)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial (uv)}{\partial x}+\frac{\partial (vv)}{\partial y}+\frac{\partial (wv)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\frac{\partial (uw)}{\partial x}+\frac{\partial (vw)}{\partial y}+\frac{\partial (ww)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

4. Results and discussion

Results were obtained for a number of locations across the furnace geometry. Fig. 5 shows plane locations in the absence of the cylinders. The distance between every two planes is the same for all the layouts to achieve appropriate comparison.

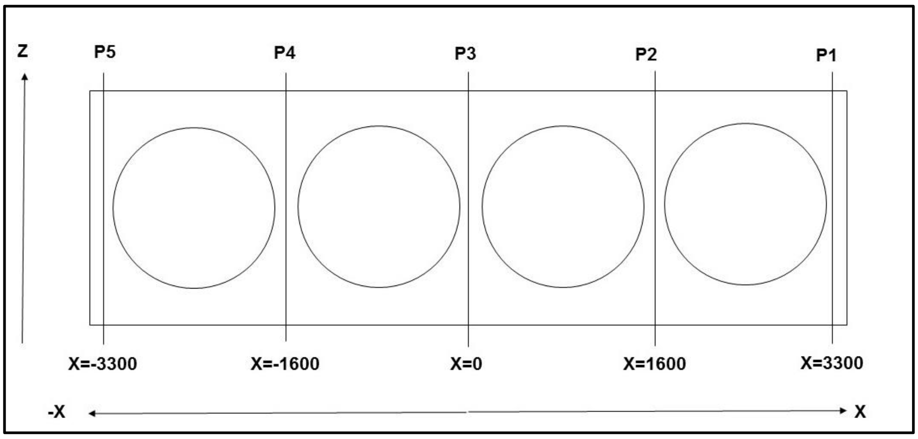
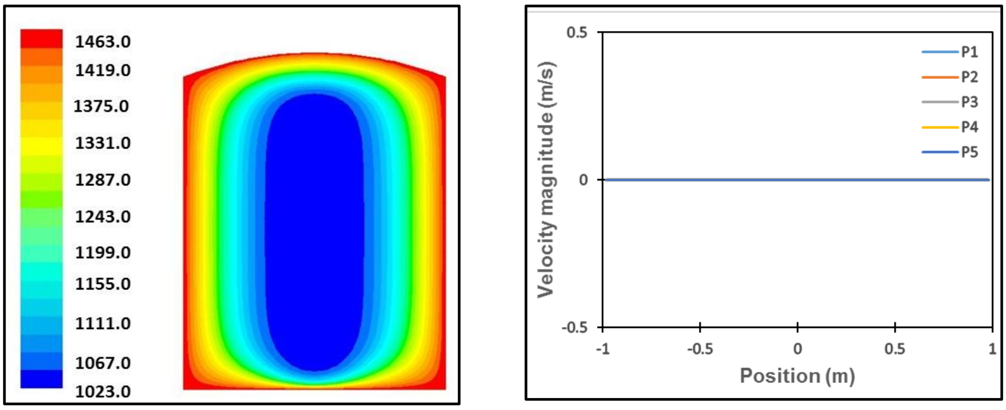


Fig.5. Lines and planes locations in the absence of the cylinders, (all dimensions are in mm).

The results presented in this study include temperature contours for the six different layouts at plane 3 (P3), which is in the middle of the geometry. The velocity charts were taken at the five different locations along the furnace geometry.

4.1 Conditions without using the rotating cylinder technique

During the early stages of the soaking cycle, the hydrogen enters in a turbulent state, i.e. Re >10,000, as a consequence of the high flow rate (not disclose due to confidentiality) at which the flow is injected through the pipe, Fig 1. However, the flow quickly becomes transitional as its temperature increases, density starts falling, and its velocity decreases as it exits the pipe and expands into the spaces under the inner covers and the furnace bell. The gas velocity continues to fall as it moves through the fluid domain inside the furnace cavity. The low gas velocity, high temperature and high concentration of hydrogen produce a laminar flow for the majority of the annealing cycle. The temperature contour and the velocity profile shown in figure 6 (A and B), demonstrate the static nature of the atmospheric gas inside the furnace cavity.



A B

Fig.6. A, Temperature contour at plane 3 (shown in Kelvin). B, Velocity profile at the five different locations across the geometry.

It can be observed from the temperature contour the temperature gradients between the furnace centre and the heating elements on the wall is high, due to the static nature of the process and the lack of fluid motion. The absence of the fluctuations and the zero velocity magnitude indicates the lack of turbulence in the fluid domain, Fig. 6B, which contributes in increasing in hotspots formation especially during long operation conditions and the failure in one of the heating elements.

4.2 Conditions using the rotating cylinder technique

Turbulence in fluid mechanics is irregular and characterised by velocity fluctuations [23]. These fluctuations mix the fluid and enhance convection. Velocity charts, Fig. 7 (A, B and C), show fluctuations in velocity magnitude at five different locations across the geometry when using the rotating cylinders technique. This is due to the continuous growth of the fluid around the cylinder due to its rotation, which generates vortices. The vortices at various scales, developed continuously within the fluid domain and travel to the surrounding areas [24], thus generating turbulence that enhances the energy transfer. The changes in velocity charts are associated with vortex boundaries. The zone in which the fluid flow is emanating from the stirrer displays the maximum values of turbulence. Fig.7 confirms that turbulence is introduced into the bulk of the furnace via cylinder rotation.

The resultant velocity increases with increasing the rotational speeds due to higher tangential velocity. At the highest rotational rate, inertial forces become dominant to viscous forces, and hydrodynamic turbulence is evident. Although using the high rotational velocity rate, the velocity magnitudes seem low. This is due to the big furnace size ~ (6.6 * 1.96 * 2) m and the flow constraints imposed by the furnace wall and other process equipment, which slow down the gas velocity. However, from a practical standpoint, the minimum value of 0.4 m/s seems acceptable in the presence of fluctuations all around the steel charge.

It was noticed that for those layouts where the cylinders are located vertically on the furnace base, the velocity is higher than those cases where the cylinders are installed horizontally on the furnace bell. This can be attributed to the cylinder locations near the inner covers and furnace walls, which hinder the development and the distribution of the vortices and the turbulence, even at high rotational rates.

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, gas recirculation was poor near the walls at locations P1 & P5 when using those profiles. Therefore, layout 4 seems to be the best regarding convection enhancement, although layout 2 has a friendlier technical implementation.

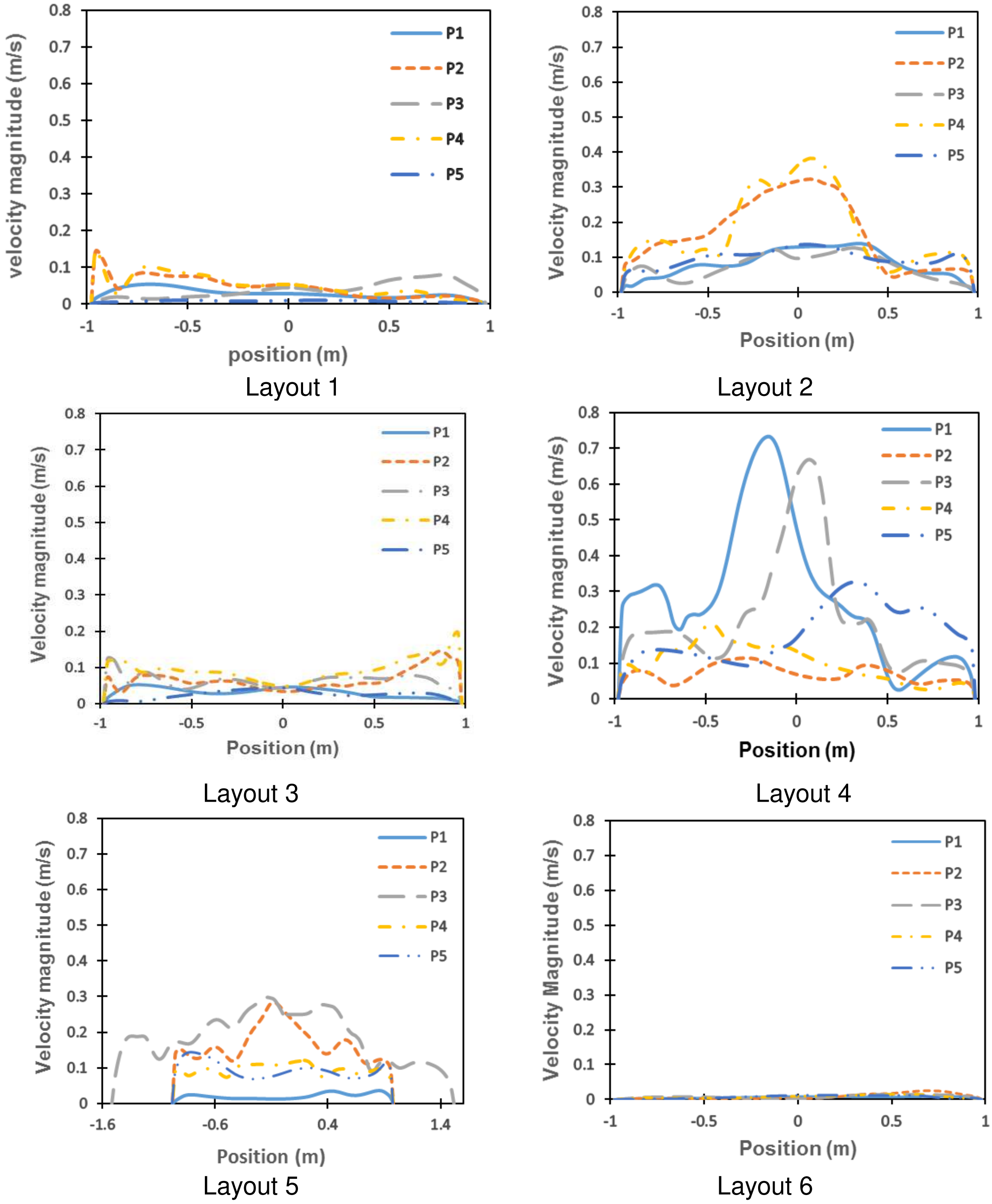


Fig.7. A, Velocity charts at rotational rate 100 rad/sec.

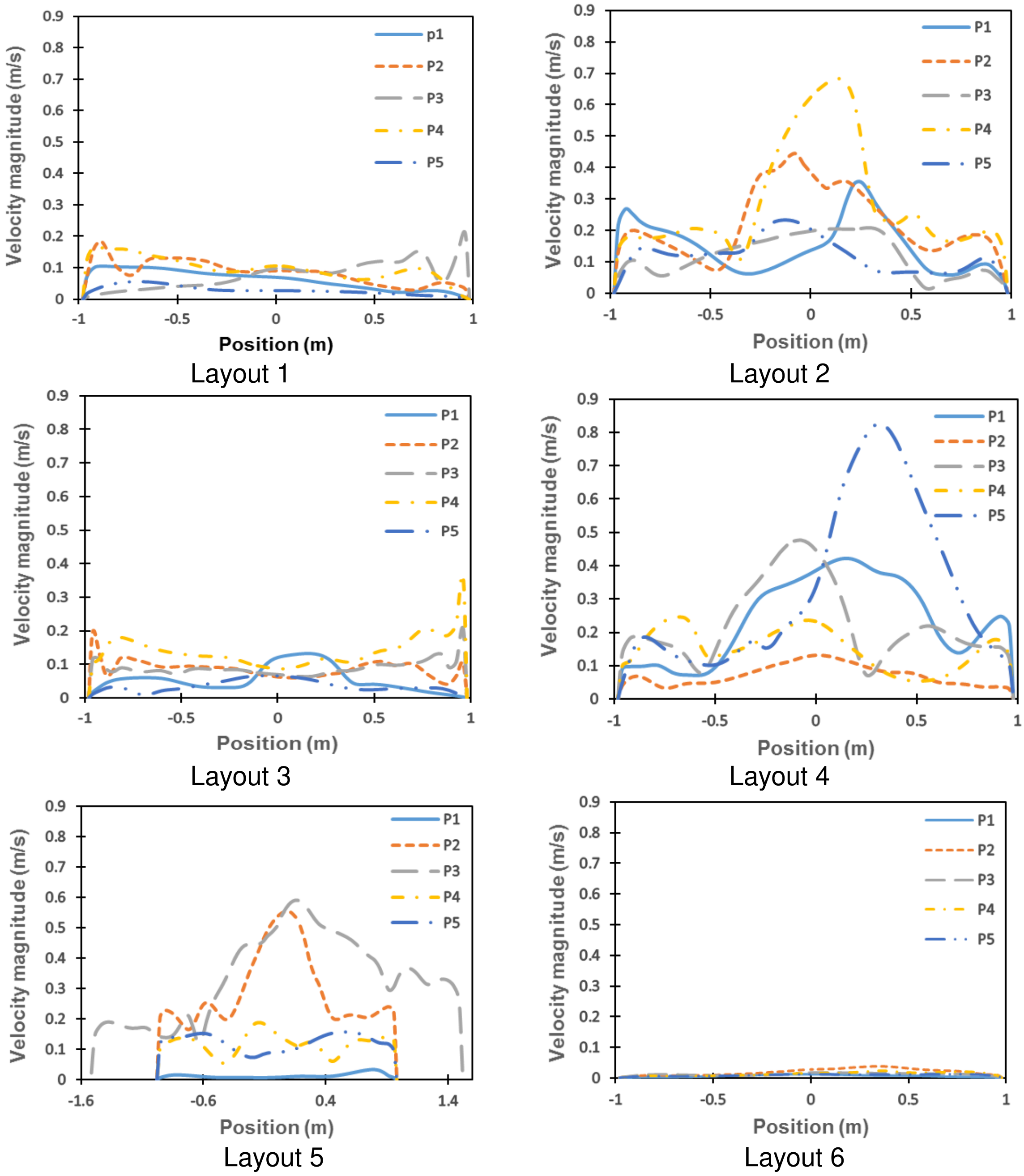


Fig.7. B, Velocity charts at rotational rate 150 rad/sec.

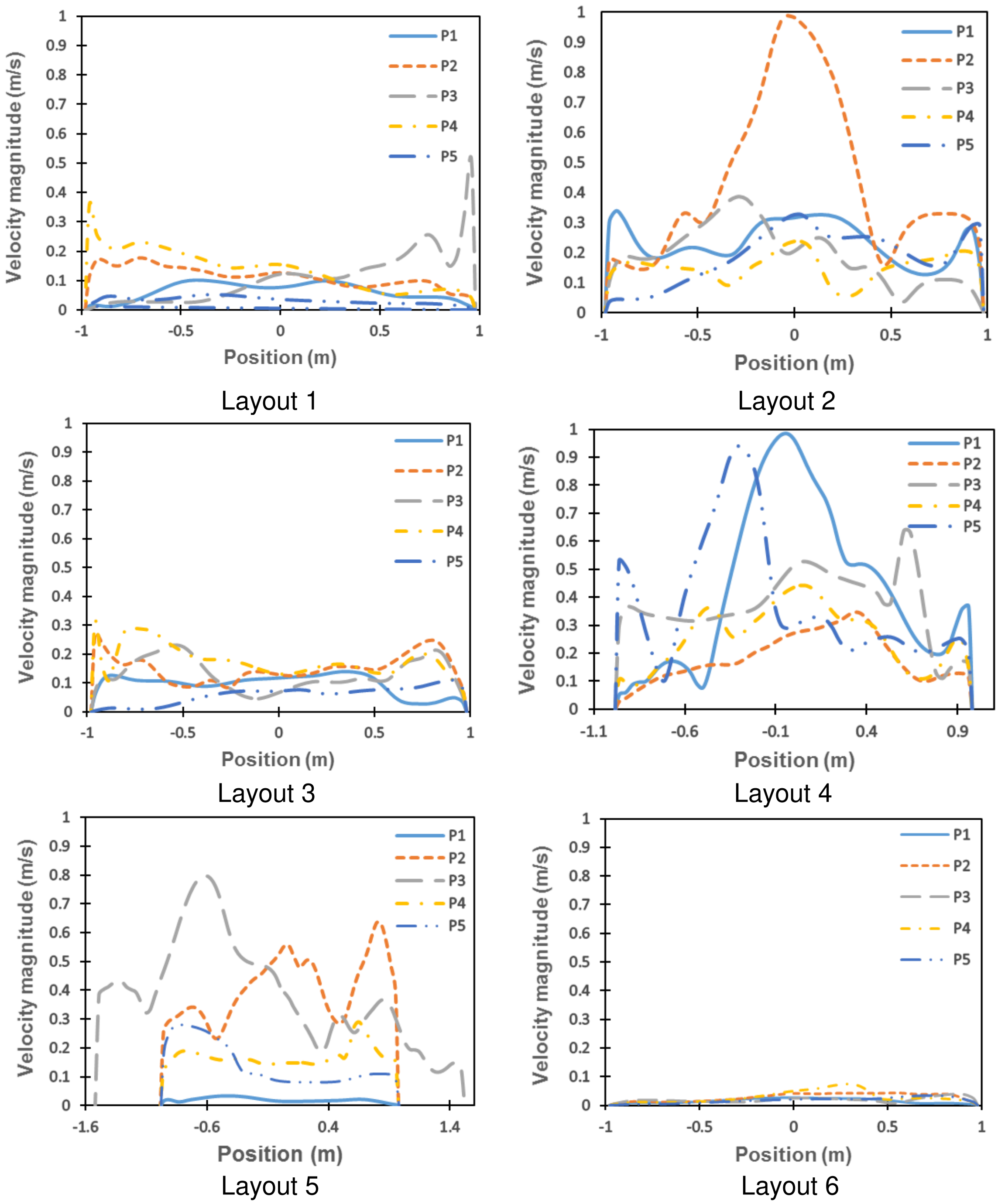


Fig.7. C, Velocity charts at rotational rate 200 rad/sec.

A typical furnace is designed to deliver an appropriate thermal cycle to the steel charge. However, thermal inefficiencies sometimes occur due to the failure in one of the heating zones, leading to less energy transfers by radiation to the charge and the need for the enhanced convection becomes indispensable.

Fig.8 (A and B) shows the temperature distribution contours for the six different layouts at plane 3 when using the technique. The temperature profile was affected noticeably by the rotational flow induced by cylinder rotation, in comparison with the same temperature profile for a case when the technique was not involved, Fig. 6. A.

The convective heat transfer and fluid mechanics are strongly connected. Fig. 8 shows that the hot gas is going towards the cylinders owing to the action of inertial forces produced by the stirring device movement. Cylinders rotation creates an enhanced thermal profile (i.e. continuously re-distributed) inside the furnace. The redistribution of the heat is sustained by the rotation technique even under the long operation conditions of the soaking cycle. Thus, the technique would help in preventing the formation of hotspots.

It can also be observed that for a particular layout the temperature gradients between the furnace wall and the furnace centre decrease with increasing the rotational speed. Because of the generation of fluid mixing and the increase in fluid velocity, which enhances the convection heat transfer coefficient and energy transfer quality [21] by means of promoting forced convection.

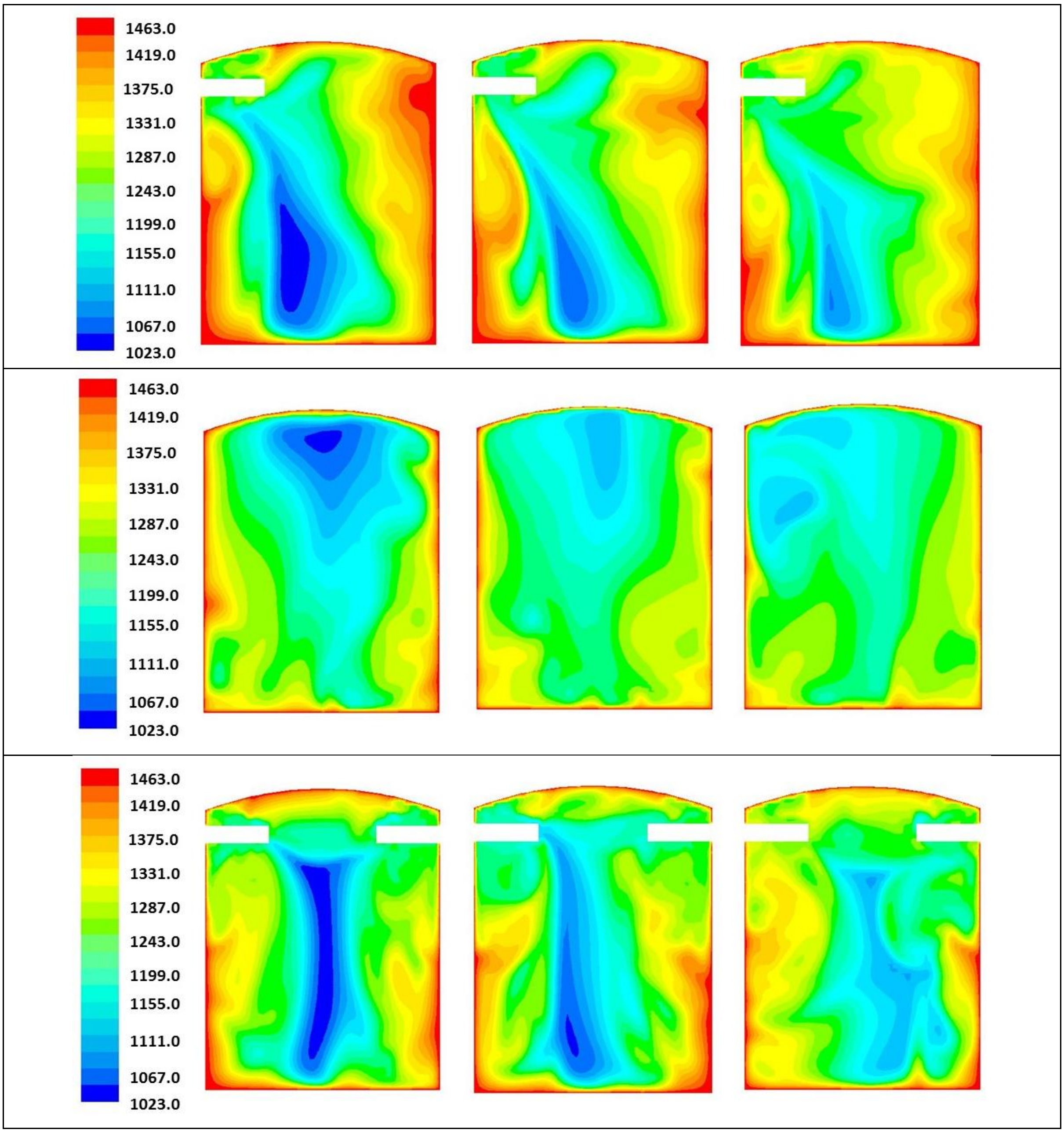


Fig.8. A, Temperature distribution contours (shown in Kelvin) for layouts 1, 2 and 3 at 100, 150 and 200 rad/sec, respectively.

However, vortex formation in layout 6 is confined at the top of the furnace, due to cylinders proximity of the inner cover and the furnace top wall, Fig. 2, which restrains the vortex development and propagation. Consequently, the rotation had a poor effect on the fluid structure in this layout.

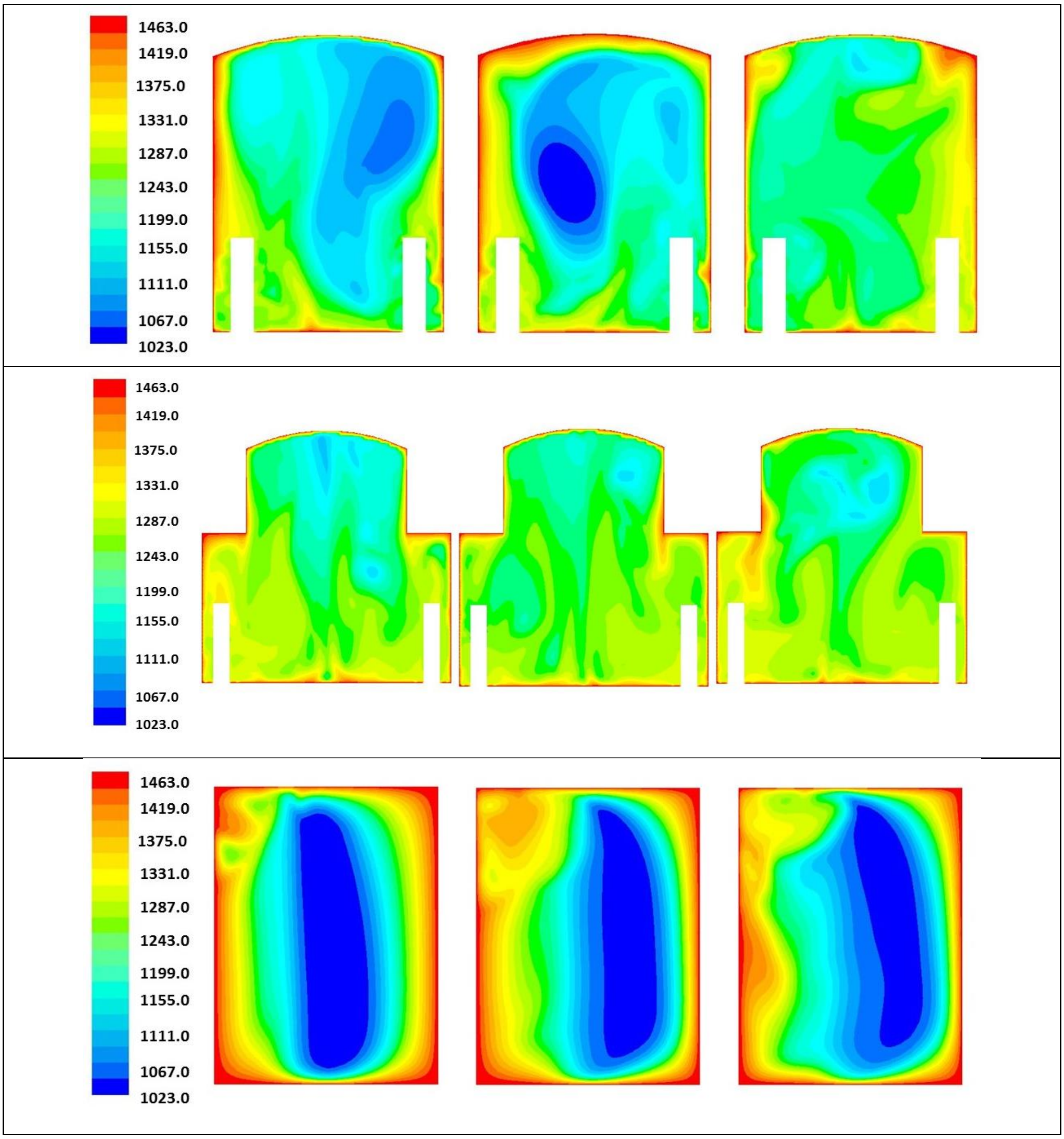


Fig.8. B, Temperature distribution contours (shown in Kelvin) for layouts 4, 5 and 6 at 100, 150 and 200 rad/sec, respectively.

5. Conclusion

This study presents a numerical investigation of using rotating cylinders to produce gas recirculation inside high-temperature coil annealing furnaces to eliminate thermal inefficiencies that occur in the event of heating element failures.

The technique was suggested as an alternative to the conventional circulation devices such as fan, whose manufacturing and installation would be dramatically expensive. The usage of this technique in high-temperature processing applications such as the HTCA has not been investigated yet.

The production of gas recirculation was achieved by generating turbulence through the vortex generation concept. Turbulence, in fluid dynamics, is characterised by velocity fluctuations.
The study conducted two numerical cases, with and without using the proposed technique. The results show fluctuations in velocity magnitudes of the fluid particles across the furnace cavity when using the proposed technique, because of the effect of cylinders rotation. In contrast, no fluctuations in velocity magnitude were observed in the case where the rotating cylinders were not employed. Moreover, results show that velocity magnitude of the atmospheric gas was 0 m/s, whereas it reaches ~ 1 m/s when using the technique. Producing gas recirculation would eliminate the thermal inefficiencies and enhance the annealing performance as well as the final product quality.
The fluctuations and fluid velocity increase with increasing the rotational speed because of the high tangential velocity. Temperature contours show noticeable changes in the thermal profile when using the rotating cylinder technique. Generating turbulence enhances gas mixing and heat distribution quality. With increasing fluid velocity, convective coefficient increases and heat transfer rate between furnace wall and the atmosphere gas increase, thus the high-temperature gradients (hotspots) decrease with increasing cylinders rotational speed.
In the six different suggested arrangements, the greatest improvement was observed in vertical configurations, with 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 build a prototype to test the validity of the concept of rotating cylinders to improve heat convection inside of an enclosed cavity.

Acknowledgments

The first author gratefully acknowledges the support provided by the Iraqi Embassy through the Cultural Iraqi Attaché during her PhD project. The research group also acknowledges the use of current facilities at Cardiff University for the CFD simulations, with special gratitude towards Prof. Tim O'Doherty, leader of the CFD group at such institution.

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