Advances in Applied Sciences
2021; 6(4): 132-141
http://www.sciencepublishinggroup.com/j/aas
doi: 10.11648/j.aas.20210604.19
ISSN: 2575-2065 (Print); ISSN: 2575-1514 (Online)

Research on Structural Optimization of Regenerative Melting Aluminum Furnace

Tao Li[1], Aiqin Li[1, *], Jiecheng Yu[1], Zhiming Guo[2], Jingyu Yan[1], Ningjing Yang[1], Yunjie Wu[2]

[1]School of Mechanical Engineering, Beijing Institute of Petrochemical Technology, Beijing, China

[2]Guangzhou Longxin Regenerative Industrial Furnace Co., Ltd., Guangzhou, China

Email address:
liaiqin@bipt.edu.cn (Aiqin Li)

To cite this article:
Tao Li, Aiqin Li, Jiecheng Yu, Zhiming Guo, Jingyu Yan, Ningjing Yang, Yunjie Wu. Research on Structural Optimization of Regenerative Melting Aluminum Furnace. *Advances in Applied Sciences*. Vol. 6, No. 4, 2021, pp. 132-141. doi: 10.11648/j.aas.20210604.19

Received: October 25, 2021; **Accepted**: October 27, 2021; **Published**: December 31, 2021

Abstract: In order to predict the performance parameters of a regenerative melting aluminum furnace new designed based on the regenerative combustion technology, the computational fluid dynamics numerical simulation method was used to study its combustion characteristics. Flow field, temperature field and mass fraction of pollutant NO were numerically simulated for the furnace by using the k-ε turbulence model, Eddy-Dissipation Concept combustion model, P-1 radiation equation, and NO_X pollutant model respectively of the ANSYS-Fluent software. The result shows a short circuit of the flue gas appears when the regenerative burner is arranged on the same side furnace wall, at the same time, the distribution of the temperature field is uneven. The researcher carried out structural transformation of the aluminum melting furnace. Compared with the furnace before modification, the furnace that the regenerative burners installed in the middle of both sides wall ensures temperature field distribution more uniform and reduction of the NO emissions at furnace outlet.

Keywords: Regenerative Aluminum Melting Furnace, Numerical Simulation, Structural Optimization

1. Introduction

The regenerative melting aluminum furnace adopts regenerative combustion technology. Regenerative combustion, also known as High Temperature and Low Oxygen Air Combustion (HTLOAC), can recover large amounts of sensible heat from combustion products and reduce emissions of harmful gases such as NOx and CO [1-3]. The regenerative burners of regenerative melting aluminum furnace are frequently commutated in a short time and alternately burned, which promotes uniform temperature field distribution in the furnace, so the temperature in the heating zone is more uniform and the cold spot is reduced [4]. In order to judge the performance of a newly designed furnace type, experiments or numerical simulation should be carry out. It is liable to damage experimental equipments or reduce the accuracy of the sensors, since regenerative industrial furnaces have higher furnace temperatures. In the research of regenerative industrial furnaces, numerical simulation can more accurately and conveniently describe the velocity field and temperature field inside the whole furnace body during the operation of the furnace. It is helpful for researchers to find and judge the location of the unreasonable velocity and temperature distribution in the furnace, analyze the cause of the problem, and find a solution to the problem [5]. Such a simulation process is cheaper and safer than experiments. Numerical simulation is generally used for the research of the regenerative melting aluminum furnace.

Francisco Cadavid et al. [6] verified the experiment on gas self-regenerating furnace with three-dimensional numerical simulation. The Gambit V_2 software was used to divide the grid and Fluent V6.2 software was used to simulate turbulence, different combustion models were used to evaluate their impact on numerical results. The momentum distribution, temperature field distribution, material distribution and emissions were compared with experimental data. The results showed that the k-RNG model predicts the formation of two concentric vortices: the first concentric vortex rises to the top of the furnace and the second one goes down and reaches the exit. It has also been found that the fuel is injected using a certain vertical inclination of the nozzle to obtain a longer and flatter flame. B. Danon et al. [7] conducted numerical studies on a furnace of a flameless burner by means of the software Fluent 6.3. Since the Reynolds number is relatively low in the cooling air flow of the cooling pipe, the prediction of the heat extraction rate of these cooling pipes is improved by treating the flow in the cooling pipe as laminar. Xiao Dan et al [8] simulated the matching at angle of incidence of air and gas of the regenerative burner by CFD software. The direction of the flame stroke and the shape of the flame are determined. At the appropriate mating angle, the combustion proceeds normally, the direction of the flame stroke is correct, and the flame shape is a good torch. At this time, the flow field of air and gas is optimal, and it is ensured that the gas is fully burned in the diffused portion.

Rao Wentao et al [9] simulated the distribution of oxygen concentration in the furnace in cold conditions with Fluent software. It is concluded that the oxygen concentration distribution in the furnace is related to the number of nozzles and the premixing of fuel and air. The structure of the burners affects the speed of mixing evenly.

2. Numerical Simulation of Regenerative Melting Aluminum Furnace

ANSYS-Fluent 15 software was used to simulate flow field, temperature field and mass fraction of pollutant NO inside the furnace in order to predict the performance parameters of the regenerative melting aluminum furnace newly designed.

2.1. Geometric Model

Heat load of the regenerative melting aluminum furnace with 15 tons of aluminum ingot is 2,500,000~3,000,000 kcal. Weight of the aluminum ingot is 20±2kg and length×width×height of it is 740×180×88mm. The overall length of the furnace is 5674 mm, the width is 5136 mm, and the height is 3400 mm. The geometry structure of the furnace is shown in Figure 1 and Figure 2.

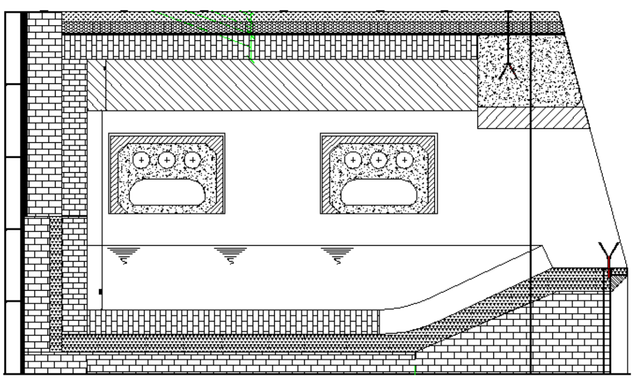

Figure 1. *Front View of the Melting Aluminum Furnace.*

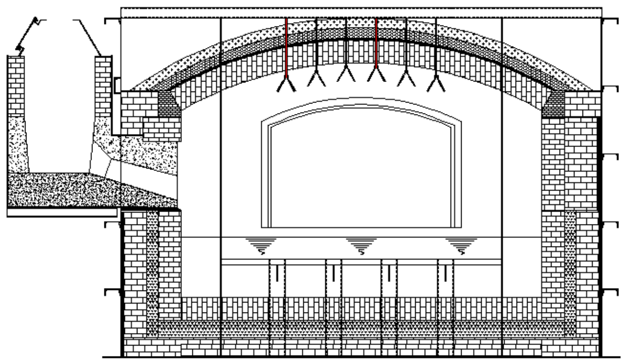

Figure 2. *Side View of the Melting Aluminum Furnace.*

Operation parameters of the burner are as follows: The volume flow of natural gas is 300 m^3/h, the pressure is 12 kPa, and the temperature is 20°C. The combustion air temperature through the reversing valve is 20°C at normal temperature, the volume flow is 3600 m^3/h, and the pressure is 4000 Pa. The temperature of the combustion air entering sprinkle fire vent reaches about 800°C after passes through the regenerative room. Natural gas and air are separately injected into the furnace for diffusion combustion. The flue gas temperature flowing through the reversing valve is 150°C, the flow rate is 4500 m^3/h, and the pressure is -4000 Pa. The temperature of the flue gas at the blasting port is equivalent to the temperature of the furnace, which is about 1150°C. The furnace temperature is approximately 1150°C to 1200°C. Parameters of air and natural gas are shown in Table 1.

Table 1. *Operation Parameters of Burner.*

Sr. No	Parameter	Value
1	Volume Flow (Natural gas), m^3/h	300
2	Pressure (Natural gas), kPa	12
3	Temperature (Natural gas), °C	20
4	Volume Flow (Air), m^3/h	3600
5	Pressure (Air), kPa	4
6	Temperature (Air), °C	20
7	Temperature (After Air Preheated), °C	800

2.2. Governing Equations and Numerical Methods

3 D model of the furnace was created with solidworks software and then import it into ICEM software to set unstructured grid. The middle aluminum block is set as wall, the air inlet is set to pressure-inlet, the natural gas inlet is set to pressure-inlet, the outlet is set to pressure-outlet, the other faces are set as wall, and finally numerical simulation of the drawn grid in Fluent software to simulation.

The Fluent 13 software was used to simulate flow field, temperature field and mass fraction of pollutant NO in the furnace. Three-dimensional Numerical Simulation were performed using Reynolds Averaged Navier-Stokes and the k-ε turbulence model, the EDC combustion model, the P-1 radiation model and the NO_X thermodynamic reaction generation model were combined application for simulation. Set the pressure of natural gas as 12000 Pa, and that of air as 4000 Pa, and set pressure as -4000 Pa at the outlet. The inner aluminum ingot is set as a wall absorbing heat continuously, and the equilibrium temperature is 660°C (the melting point of aluminium). A pressure-velocity coupled SIMPLE algorithm was used, where the turbulence model couples the radiation model every 10 times calculations.

(1) Combustion Model

The material composition transfer model used in the combustion model is as follows:

$$\frac{\partial}{\partial t}\left(\rho \vec{v} Y_i\right)+\nabla\left(Y_i\right)=-\nabla \vec{j}_i+R_i \quad (1)$$

We can correct the formula and get the following formula for turbulence:

$$J_i=-\left(\rho D_{i,m}+\frac{\mu_t}{\sigma_T}\right)\nabla Y_i \quad (2)$$

Eddy-Dissipation Concept used turbulence to control the rate of the reaction.

$$R_{i,1} = M_{w,i}\sum_{i=1}^{N_r} R_{i,r} \quad (3)$$

where: $M_{w,i}$ —— the molecular weight of the i-th substance; $R_{i,r}$ —— the molar rate of roduction/decomposition of the i-th species in the r-th reaction, mol/s; N_r ——the number of chemicals that react r, ind.

(2) NO_X reaction generation model

Only a small amount of NOx is produced when high temperature air is burned, and the main pollutant is NO. It does not have a large effect on temperature, velocity, and major component concentrations. The thermal NO_X transport control equation is as follows:

$$\frac{\partial}{\partial t}\left(\rho Y_{NO}\right)+\nabla\left(\rho \vec{v} Y_{NO}\right)=\nabla\left(\rho D \nabla Y_{NO}\right)+S_{NO} \quad (4)$$

The rate of NO generation calculated using the quasi-steady state assumption is:

$$\frac{d[NO]}{dt}=2k_1[O][N_2]\frac{\left(1-\frac{k_{-1}k_{-2}[NO]^2}{k_1[N_2]k_2[O_2]}\right)}{1+\frac{k_{-1}[NO]}{k_2[O_2]+k_3[OH]}}\left(\mathrm{gmol/m^3\cdot s}\right) \quad (5)$$

2.3. Analysis of Simulation Results

We analysed the parameters of the plane where the inlet and exit are located separately. The velocity distribution at the entrance and exit is shown in Figure 3 and Figure 4. It is found that the areas with higher flow rates are mainly distributed at the inlet and outlet. by analyzing Figures 3 and 4. Since the differential pressure between the inlet and outlet is large, the division speed in the Y direction is small, and there is a large division speed of 20 m/s in the X direction. Since inlet and the outlet of the regenerative furnace are disposed on the same side, a short circuit phenomenon is inevitable. Part of the hot flue gas ejected from the burner spread in the Z and Y direction, and be extracted at the exit. Part of the heat of the flue gas was not fully utilized before it was exhausted.

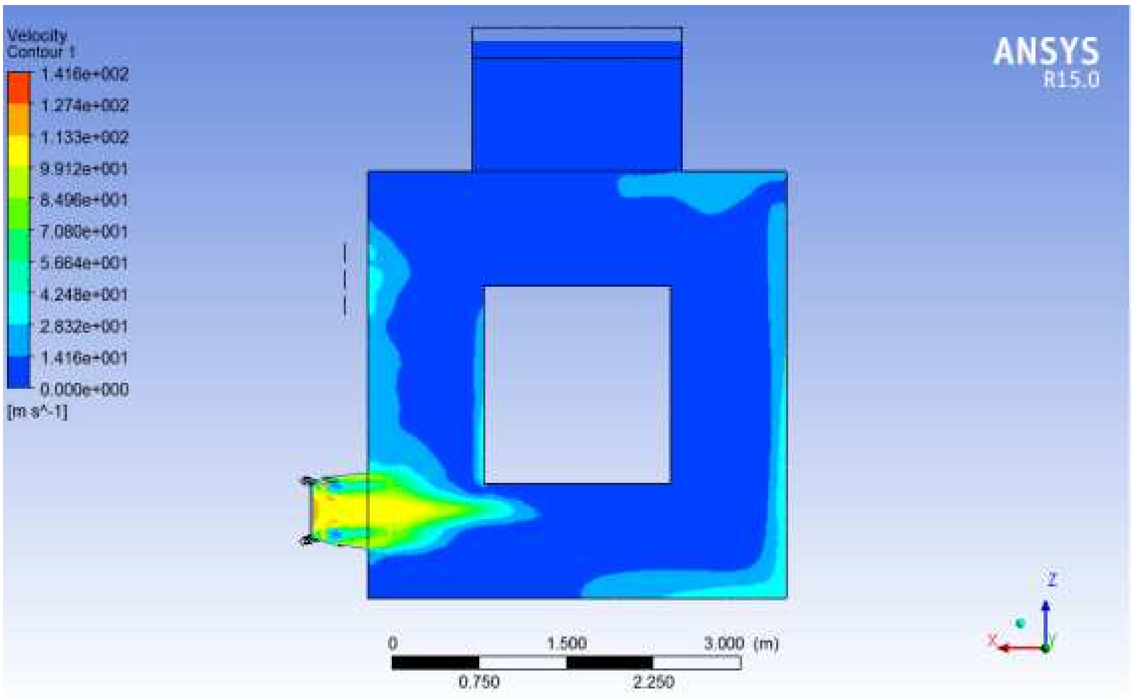

Figure 3. *Contours of Velocity Magnitude in the Inlet (m/s).*

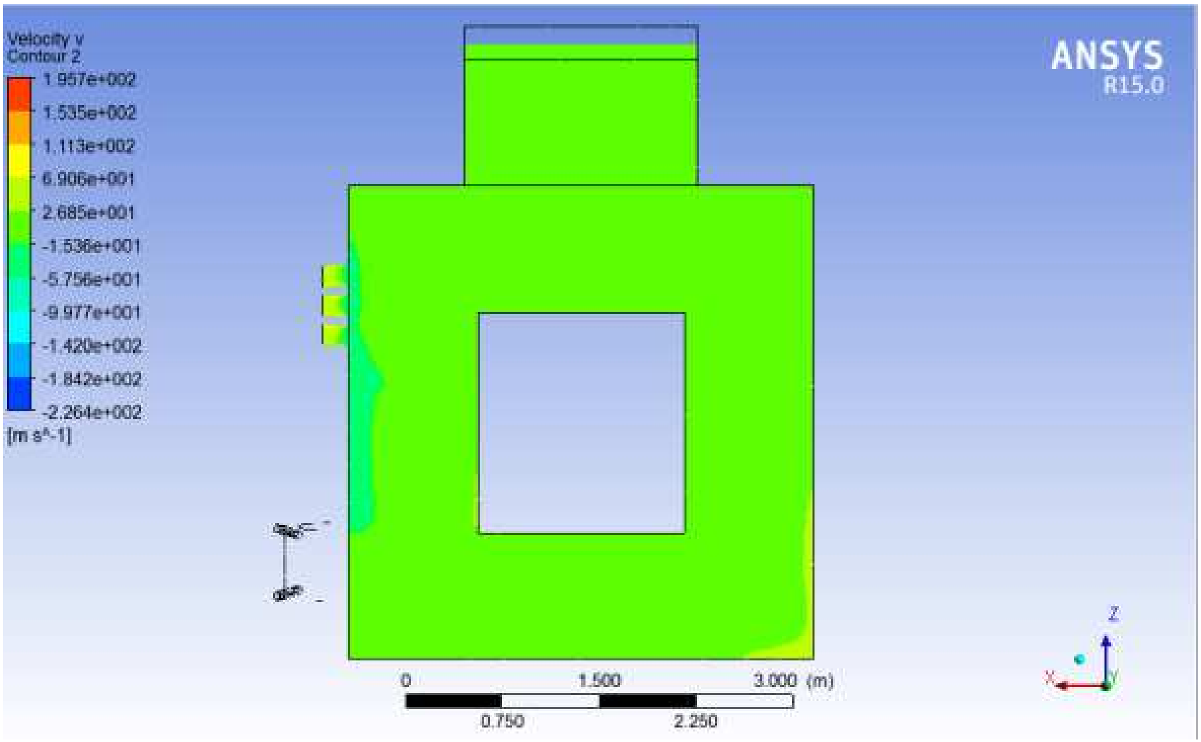

Figure 4. *Contours of Velocity Magnitude in the Outlet (m/s).*

Distribution of temperature fields at the inlet and outlet are shown in Figures 5 and 6: Since the flue gas in the rear of the regenerative furnace hardly flows, a high temperature zone is formed in the lower right corner of the furnace. The flue gas flows slowly in the protruding part of the front end of the furnace, and heat is mainly transferred through heat conduction, so the temperature of this part is lower. After the flue gas flows in the Z direction, it reaches the outlet and is exhausted. Distribution of temperature fields on the ZX plane is very uneven in the inlet and the outlet, which is not conducive to the simultaneous melting of the aluminum ingot.

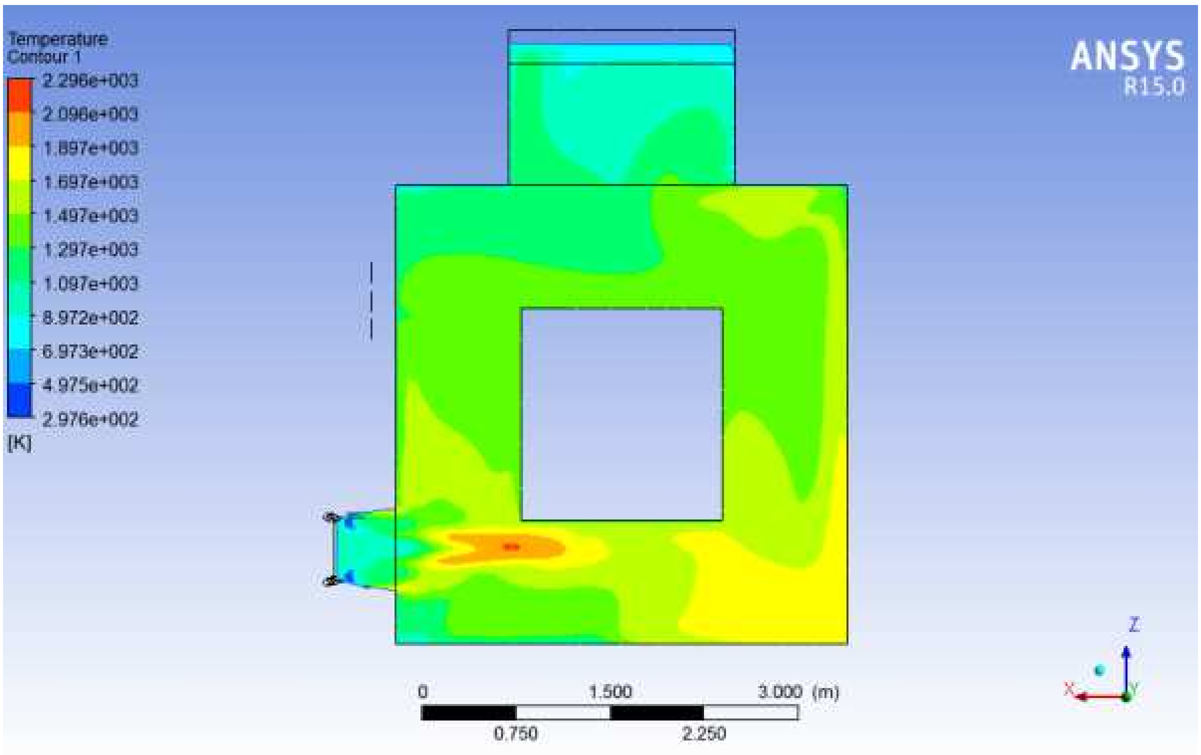

Figure 5. *Contour of Temperature in the Inlet (°C).*

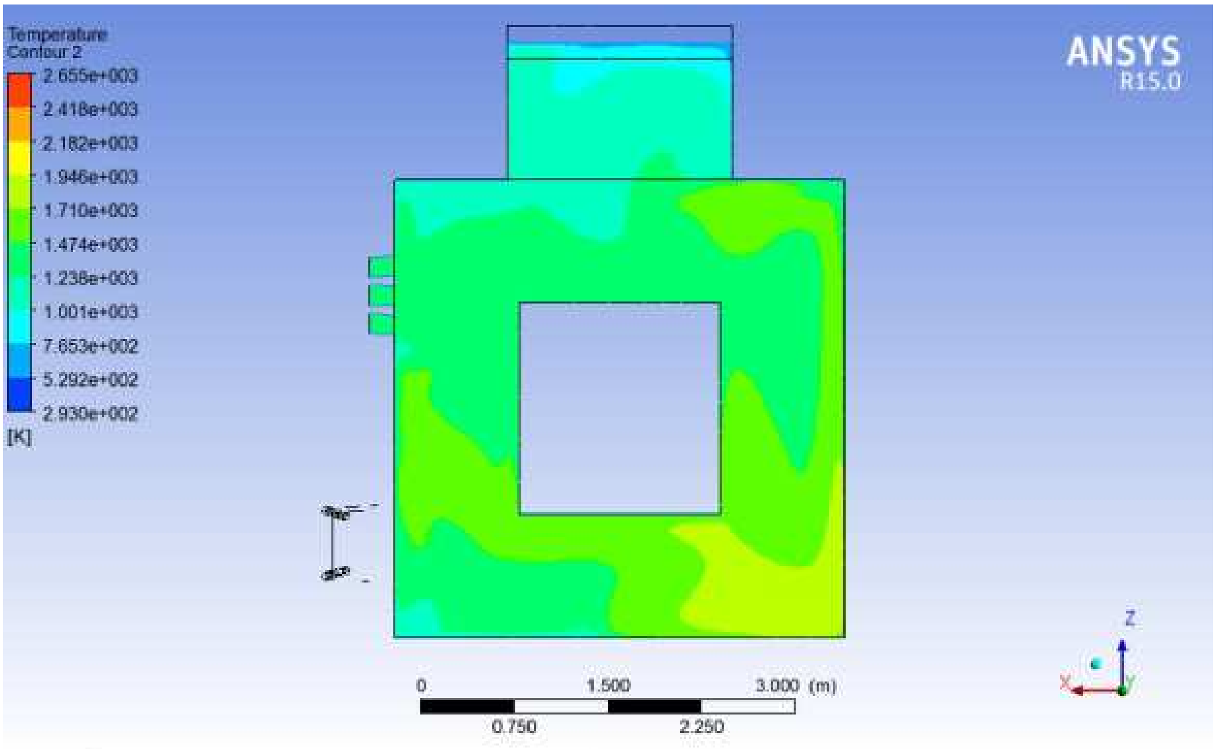

Figure 6. *Contours of Temperature in the Outlet (°C).*

As can be seen from the contour of temperature in the inlet, the highest point of temperature is at the end of the flame, approximately 1/3 of the width of the furnace. When the furnace is filled with aluminum ingots, the flame ejected from the burner will be directly sprayed onto the aluminum ingot. The aluminum ingot heated directly by the flame will melt first, while the aluminum ingot at the farthest end of the burner is heated more slowly, which greatly reduces the productivity of the furnace.

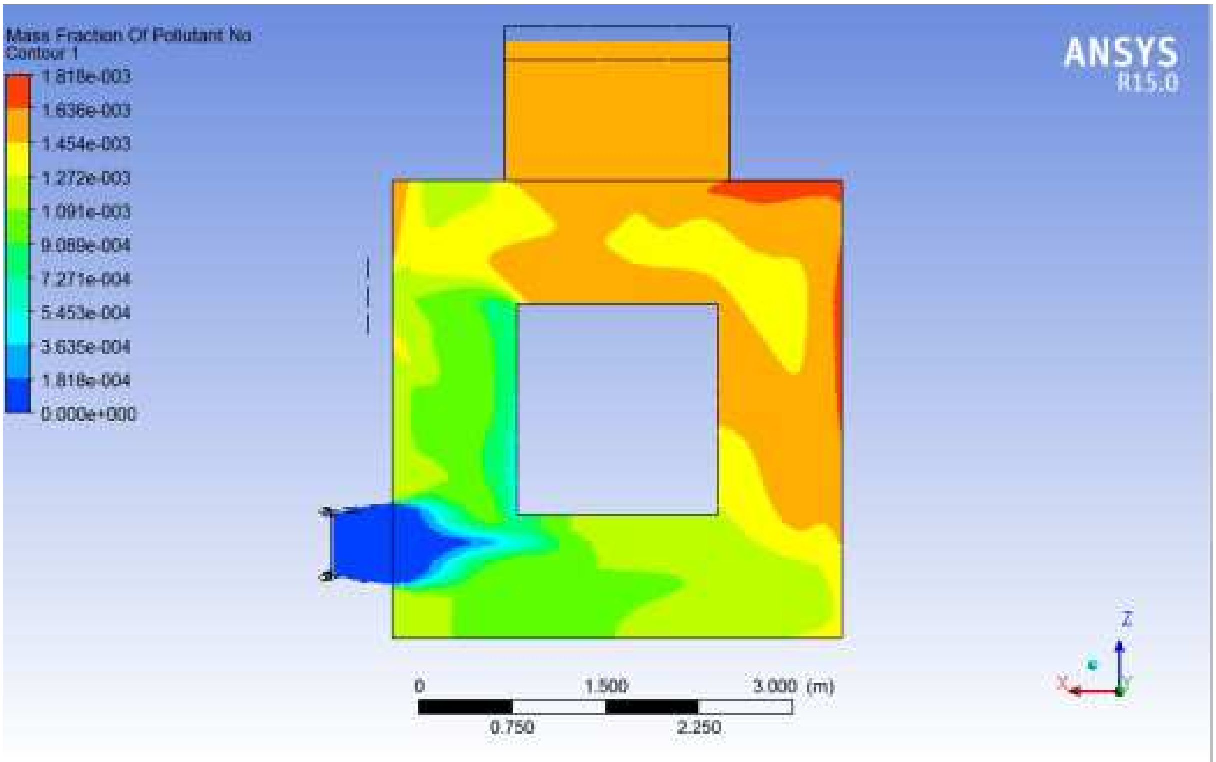

Figure 7. *Mass Fraction of Pollutant NO Contour in the Inlet.*

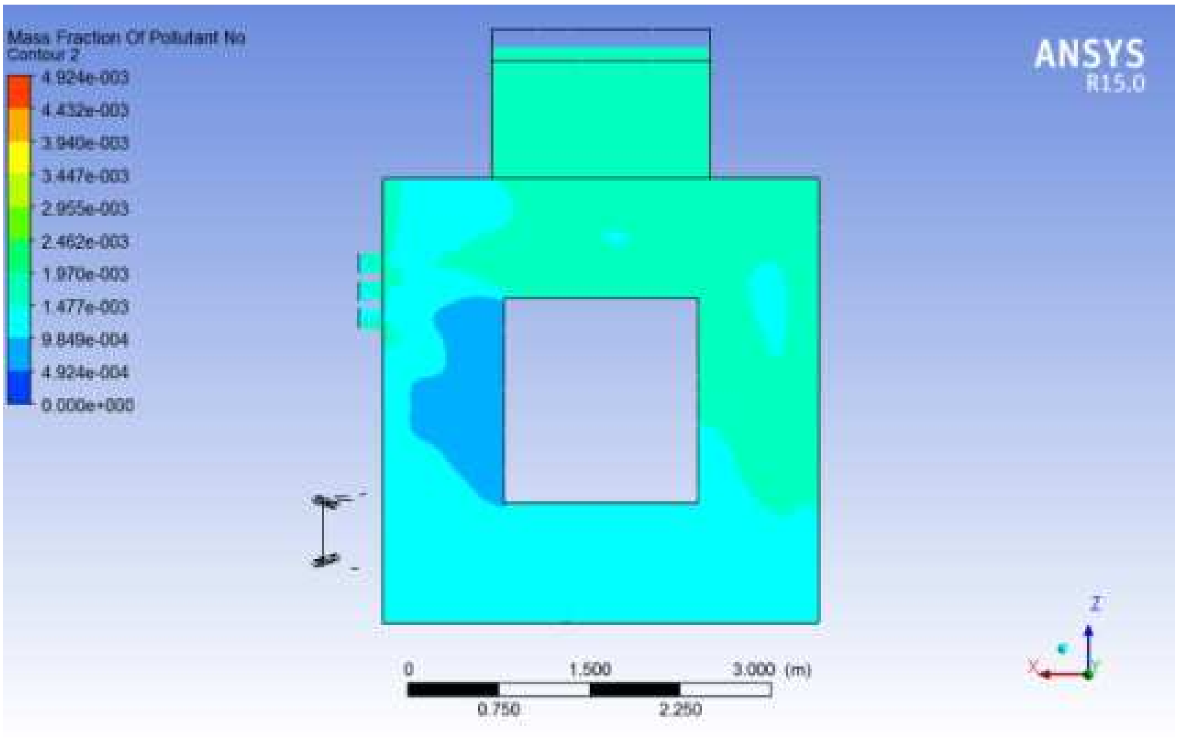

Figure 8. *Mass Fraction of Pollutant NO Contour in the Outlet.*

The NO distribution at the inlet and outlet is shown in Figures 7 and 8: Due to the uneven distribution of the temperature field, more NO is produced. The flue gas flowing brings NO along the right edge to the front to form a recirculation zone, It cause NO accumulate in the front just as shown in Figure 8. Due to the poor gas flow effect in the front protruding space, it is extremely difficult for NO to be exhausted. Therefore, there is also a large amount of NO accumulated here. Since the inlet and outlet of the regenerative burner are on the same side, part of the hot flue gas is directly exhausted from the outlet under the influence of the flue gas short circuit. So the mass fraction of NO here is also lower compared with the other side.

3. Structural Optimization of Aluminum Melting Furnace

Since the regenerative burner is arranged on the same side, it will inevitably cause a short circuit of the flue gas, so a larger inlet pressure is needed to avoid this situation. The researcher carried out structural transformation of the aluminum melting furnace. The regenerative burners were placed in the middle of both sides the furnace body in order to make temperature field distribution of the furnace more uniform. The geometry of the modified furnace body is shown in Figure 9.

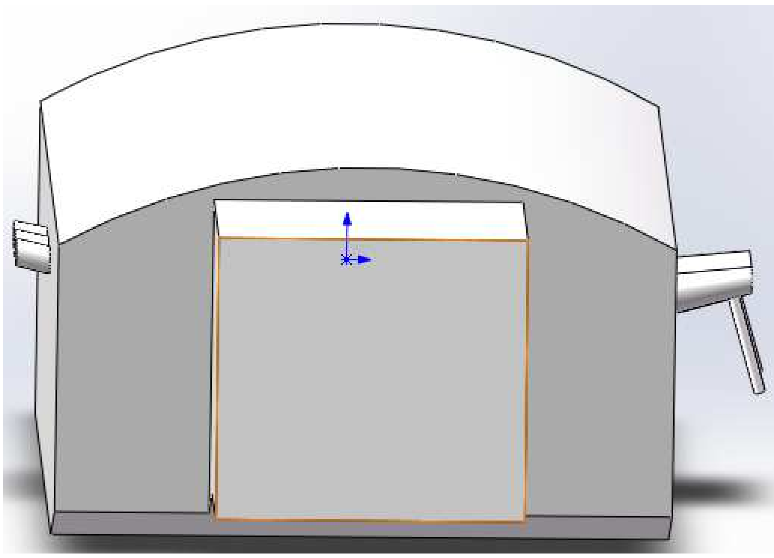

Figure 9. *Optimized 3D Solid Structure.*

Using the same simulation method as described above, flow field, temperature field and mass fraction of pollutant NO was obtained inside the modified furnace body.

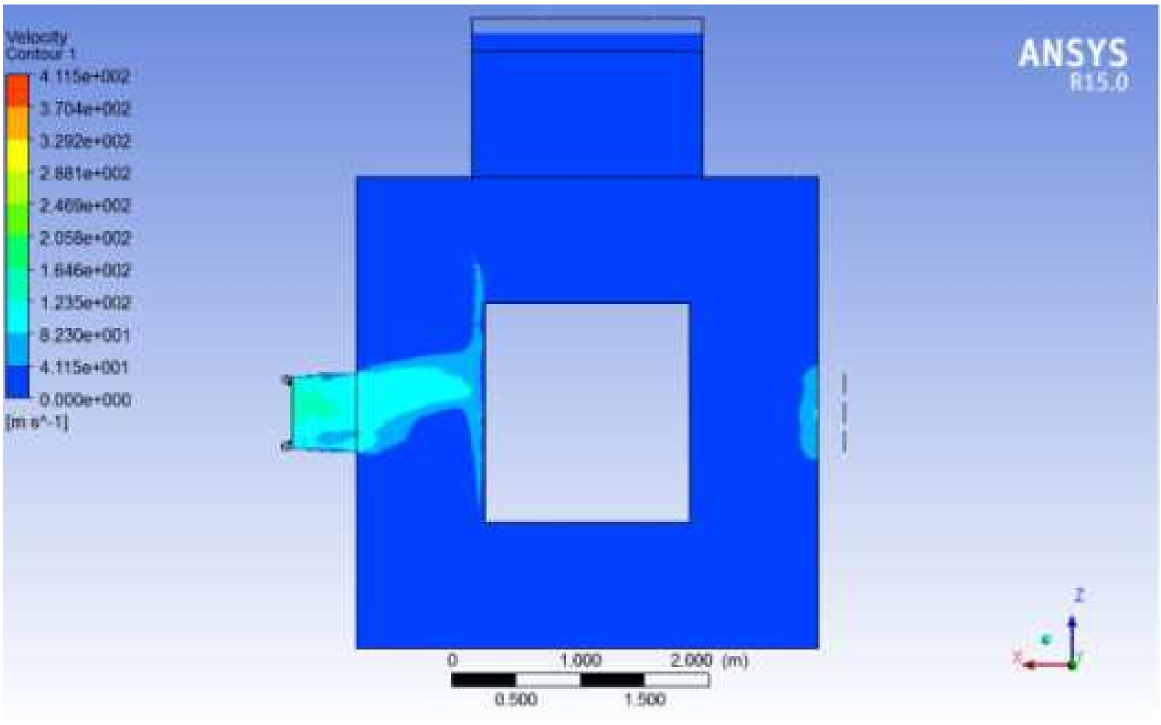

Figure 10. *Contours of Velocity Magnitude in the Inlet (m/s).*

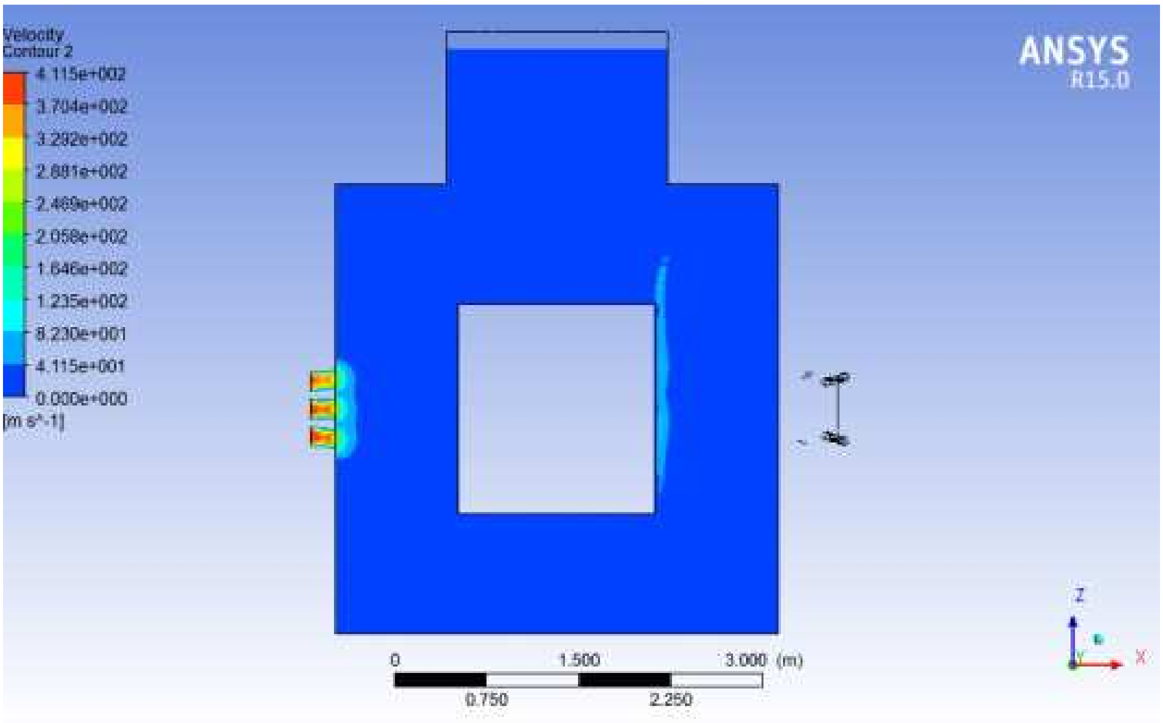

Figure 11. *Contours of Velocity Magnitude in the Outlet (m/s).*

Comparing Figures 10 and 11 with Figures 3 and 4, the flue gas formed by the combustion of natural gas and air in the burner enters the furnace, and is automatically separated for the blocking of the aluminum ingot. Since the outlet is disposed opposite, the flue gas is directly exhausted from the exit. Similarly, since the velocity generated by the gas pressure is mainly in the X direction, the velocity in the Y direction generated by the pressure is smaller, and the flue gas in the furnace has a speed of 20 m/s in the X direction. This is exactly the same as before.

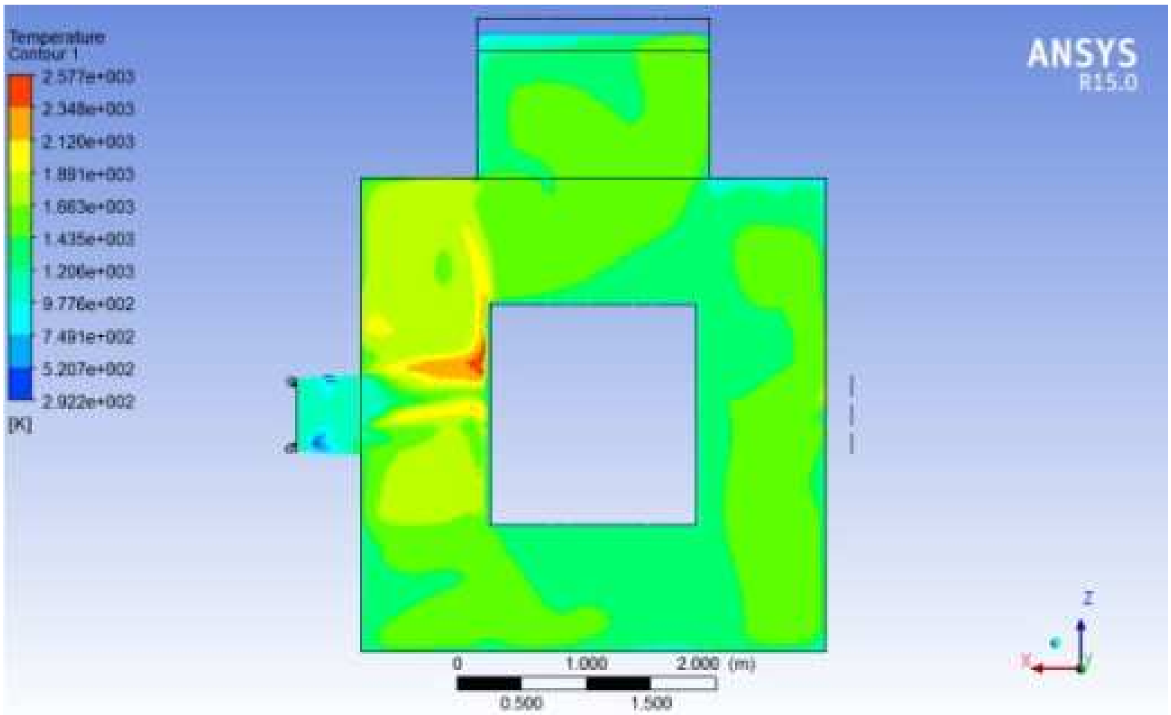

Figure 12. *Contours of Temperature in the Inlet (°C).*

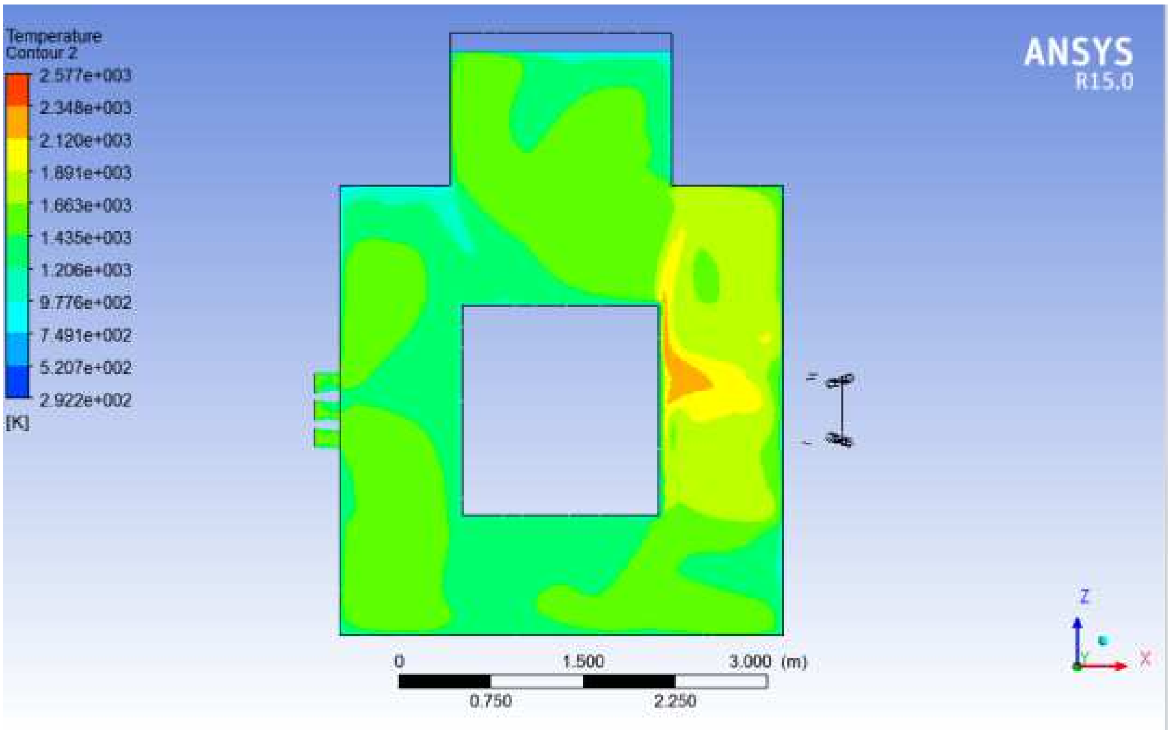

Figure 13. *Contours of Temperature in the Outlet (°C).*

Comparing Figures 12 and 13 with Figures 5 and 6, since the flue gas is ejected from the blast port, it spreads to both ends due to the blocking of the aluminum ingot. Therefore, it can be seen that the temperature is transmitted to the edges from both sides, there is almost no low temperature region, and the temperature field is more uniform. At the same time, since the blast port is located at the middle portion, it is easier to bring heat to the front space when the flue gas moves in the Z direction, so the front space is also sufficiently heated. Due to the blocking of the aluminum ingot, the flame spread around. This makes the heating area of the aluminum larger, which can increase the heating area of the aluminum ingot and accelerate the melting of the aluminum ingot.

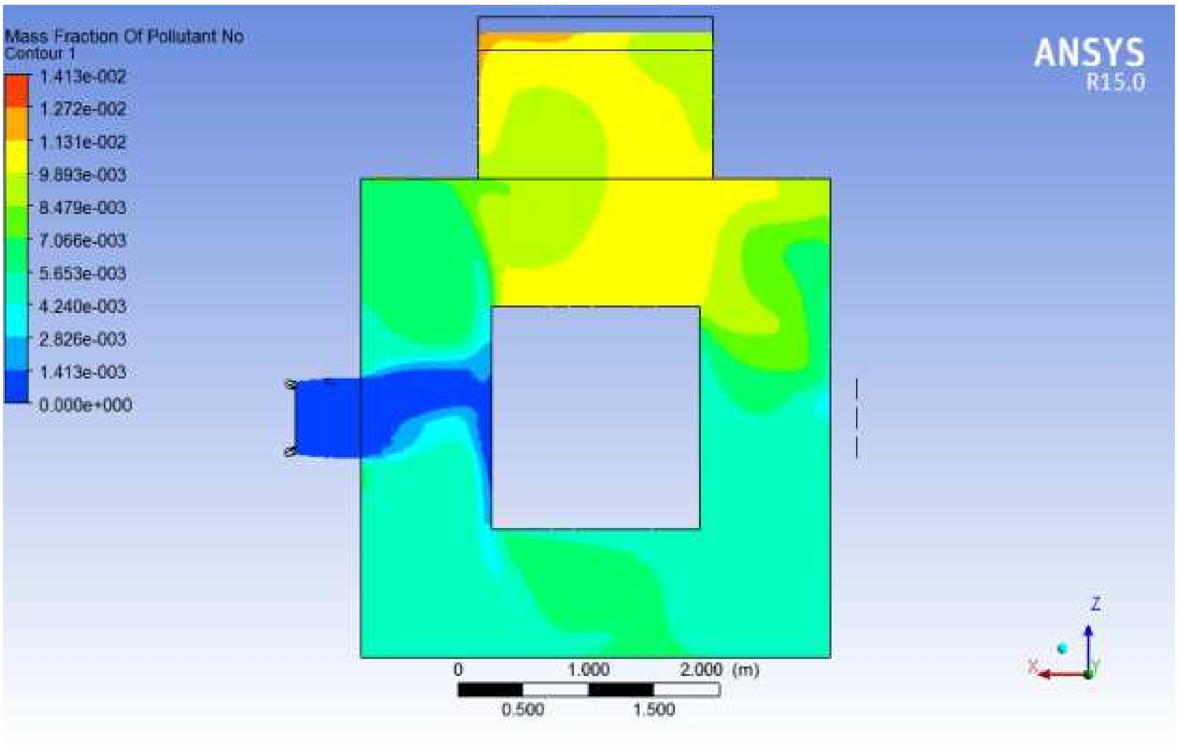

Figure 14. *Mass Fraction of Pollutant NO Contour in the Inlet.*

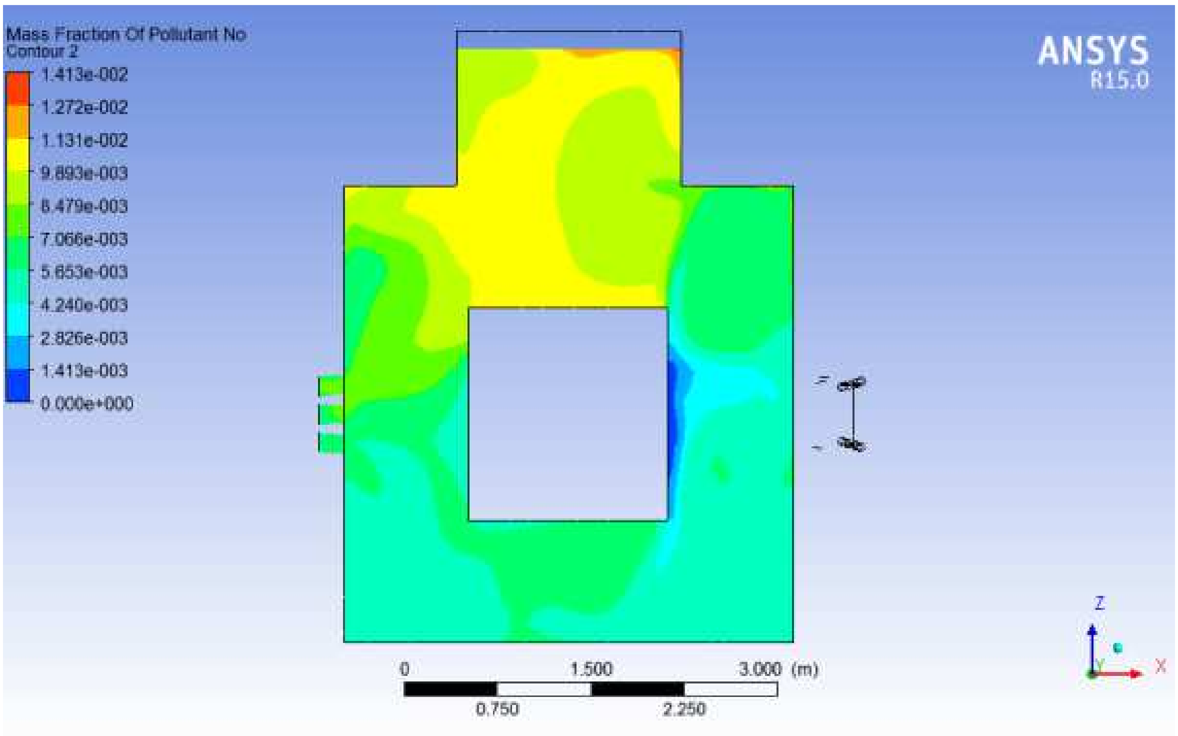

Figure 15. *Mass Fraction of Pollutant NO Contour in the OutIet.*

The NO distribution at the inlet and outlet is shown in Figures 14 and 15, Comparing Figures 14 and 15 with Figures 7 and 8, since the distribution of the temperature field is more uniform, the amount of NO generated is significantly reduced. In the inlet plane, it is reduced from 0.0001818 to 0.0001413; in the exit plane, it is reduced from 0.000197 to 0.0001413.

4. Conclusion

Three-dimensional numerical simulations were performed using Reynolds Averaged Navier-Stokes. The result shows when the inlet and the outlet of the regenerative furnace are disposed on the same side wall, a short circuit phenomenon is Xinevitable, that is, part of the heat of the flue gas was not fully utilized before it was exhausted. On the contrary, temperature field distribution of the furnace is more uniform, the regenerative burners were placed in the middle of both sides wall of the furnace body. The regenerative melting aluminum furnace modified can better meet the needs of production.

References

[1] Wang Zibing, Li Shi Cheng, Xing Hongwei, et al. Design and a application of flue gas backflushing system for regenerative heating furnace. *China Metallurgy,* vol. 29, no. 11, pp. 82-86, 2019.

[2] Experiments on pressure distribution inside regenerator of reheating furnace for rolling process. *China Metallurgy,* vol. 29, no. 9, pp. 29-32, 2019.

[3] Bu Huancun. Application of Heat Storage High Temperature Air Combustion Technology. *Journal of Iron and Steel Research,* vol. 17, no. 5, pp. 1-6, 2005.

[4] Liu Zhiqiang, Han Zheng, Wang Zhenhe. Structural Optimized for the Regenerative Burners of Little Heating Furnace. *Industrial Furnace*, vol. 26, no. 1, pp. 36-38, 2004.

[5] Lv Yiqing, Sun We, Hou Weijun, etc. Study and Design of Structure Optimization in Regenerative Burner of Reheating Furnace. *Industrial Furnace*, vol. 27, no. 4, pp. 9-16, 2005.

[6] Cadavid F, Herrera B, Amell A. Numerical Simulation of the Flow Streams Behavior in a Self-regenerative Crucible Furnace. *Applied Thermal Engineering,* vol. 30, no. 8, pp. 826-832, 2010.

[7] Danon B, Cho E S, Jong W D, et al. Numerical Investigation of Burner Positioning Effects in a Multi-burner Flameless Combustion Furnace. *Applied Thermal Engineering*, vol. 31, no. 17, pp. 3885-3896, 2011.

[8] Xiao Dan, Liu Hongxun, Yang Tao. Numerical Simulation and Parameters Optimization of Combustion Process of Air Single-Regenerative Burner. *Industrial Furnace*, vol. 34, no. 6, pp. 49-51+55, 2012.

[9] Rao Wentao, Dun Jun, Zhang Hesheng, etc. Numerical Simulation Optimizing Research of Regenerative Burner Structure. *Industrial Furnace,* vol. 24, no. 2, pp. 5-8, 2002.