

Modeling and Analysis of Temperature Distribution in the Industrial Gas Fired Powder Coating Oven using Computational Fluid Dynamic (CFD)

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ABSTRACT: In this paper, study focused on the modeling and analysis of temperature distribution in the industrial gas fired powder coating oven having dimension of 2700 x 1900 x 2700 mm³ is analyzed using Computational Fluid Dynamic (CFD). The CFD analysis of existing oven with few modifications in geometry is done to achieve uniform temperature distribution. For CFD analysis ANSYS 14.5 is used. This study is particularly focused on the variations of pressure and temperature inside the oven. With the existing geometry of the oven, it is found that there is non-uniform temperature distribution inside the oven. Therefore, the geometry of an oven is modified. The Inlet opening to the oven is made adjacent to the bottom of the oven and inlet to oven through the perforated bottom. From the result, it is cleared that the inlet to the oven from slit adjacent to bottom and perforated bottom inlet shows uniform temperature distribution in the oven.

I. INTRODUCTION

Now a days, powder coating technology is used for engineering components to improve the life and surface finish of the components. Coating is a process of covering a surface of objects, called as substrate. The purpose of coating may be functional, decorative or both. The two important types of coating are [1]: Liquid coating technology (wet), which has been used for more than two centuries and Powder coating technology (dry), which has been used in Industries for some 30 years. The use of Powder Coating technology has been increased tremendously in recent years due to its relatively high performance over liquid coating technology. Various types of equipment are available for powder coating to small and large end users. The parts which need to be coated are grounded neutral so that the particles projected from spray gun can adhere to the parts and are held there until curing process is done in the oven [2]. The result is a uniform, durable, high-quality finish. The present analysis of oven is done at GUKSS Industries, Amravati. The geometry of gas fired convection oven is made and boundary conditions are analyzed. The problem in the oven at GUKSS Industries is uneven distribution of temperature. The CFD analysis is done to achieve uniform temperature distribution throughout the oven.

In 2003, Nantawan Therdthai et al. [3] suggested to modify the oven configuration for better heat distribution and provided constructive information to achieve the optimum baking temperature profile by manipulating energy supply and airflow pattern. Zinedine Khatir et al. [4] have studied the application of computational fluid dynamics (CFD) and oven design optimization and reduce the effective baking time and hence improve the energy efficiency of the process. Pumpruk Satthave [5] analyzed CFD modeling and validation of temperature distribution in the IR oven and found that IR oven has better efficiency than the other traditional convection oven particularly for large objects having high emissivity.

II. CFD MODELING AND SIMULATION

2.1. Oven geometry

The dimensions of the industrial oven are a length of 270 cm, a width of 190 cm and a height of 270 cm. There is one burner which is situated in the centre of the top of the oven which has been designed to generate hot air from the combustion of natural gas. The hot air is then circulated through the supply duct by the air circulation fan and into the heating chamber. After the hot air has passed through the heating chamber, it then returns to the burner to be reheated, and finally back into the supply duct via a recirculation fan located on top of oven. The whole oven is surrounded by insulation made of glass wool, which is 10 cm thick. This is to stop the heat escaping to the atmosphere and make the oven more efficient. Modeling assumptions are taken into consideration and simplified geometries of oven with proposed modification are made in ICEM 14.5 as shown in Figure 2.1.

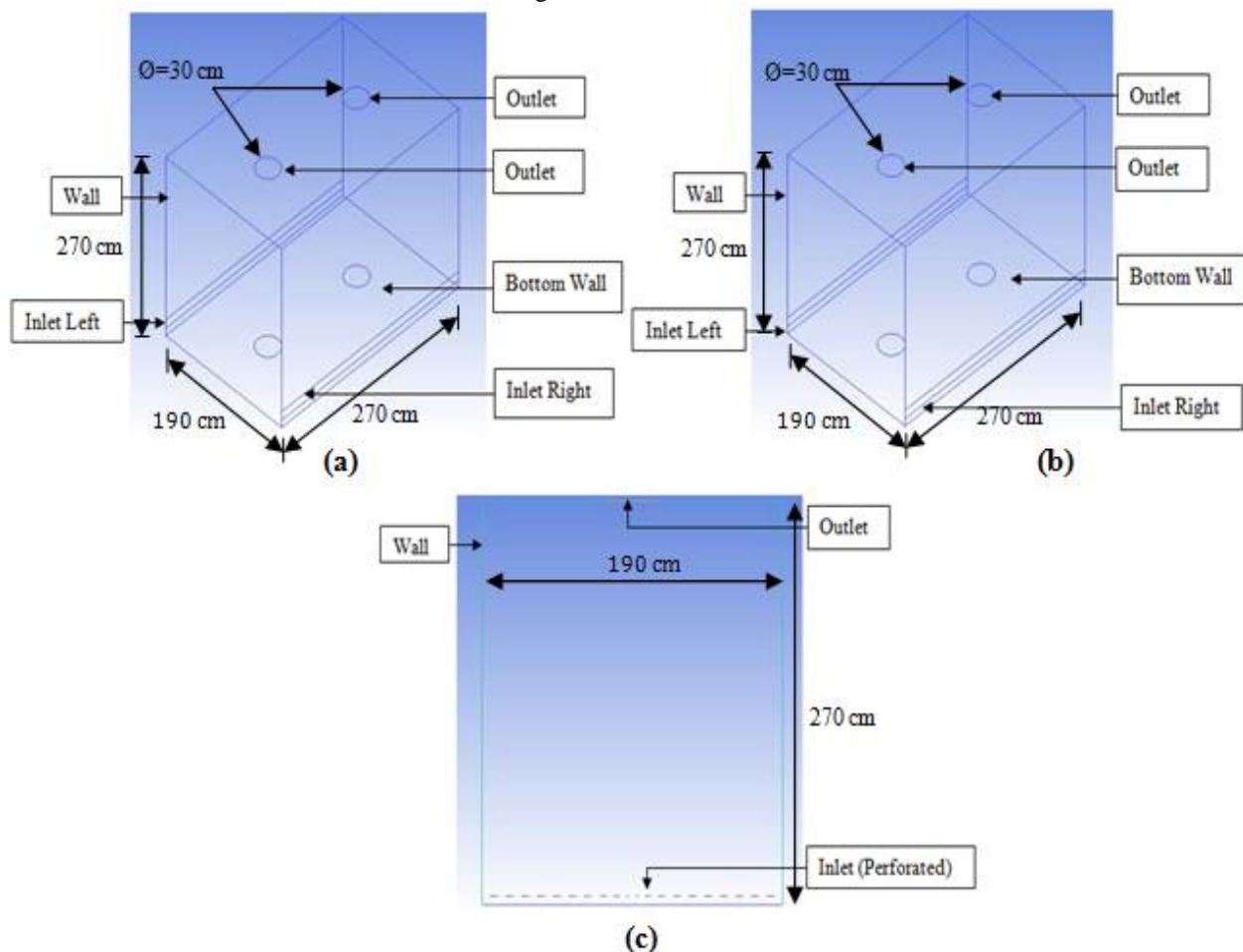


Figure 2.1:(a) Geometry of existing setup, (b) Geometry with position variation of Inlet Slit, (c) Geometry with inlet through perforated bottom

2.2. Modeling assumption

A three-dimensional model of oven is taken as the calculation domain. As the oven has a recirculation fan installed, the flow inside the ducts would not be of laminar flow. This fan will cause the air in the oven to be influenced by forced convection. Since the 3-D model is chosen, gravity is considered therefore natural convection is also included. Creating

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Vol. 6, Issue 6, June 2017

the recirculation fan in a 3-D geometry is difficult to model because Fluent would not recognize that the flow could circulate so some modifications to the geometry were made. In order to overcome this problem, it is assumed that the air would exist in the system where it was drawn into the fan and enter through the supply duct. The fan inside the oven is represented with the pressure outlet and inlet which creates flow of air.

2.3. Boundary Conditions

Boundary conditions are a very important aspect of modeling in Fluent. There are four types of boundary conditions affecting the oven; they are pressure inlet, pressure outlet, temperature inlet and wall properties. To represent the burner in oven, an inlet condition with a specified temperature that corresponds to the burner is chosen. By choosing this type of condition it enabled the heat to affect the cooler air exiting the heating chamber. As the fan was removed from the oven geometry the pressure difference created by the fan was modeled using the pressure inlet and outlet. The values for these boundary conditions are shown in Table 2.1

Table 2.1: Boundary Conditions for Inlets and Outlets

Boundary Name	Boundary Type	Temp (°K)	Pressure (Pa)	Turbulence type
Inlet_Left	Pressure inlet	500	150	k-ε
Inlet_Right	Pressure inlet	500	141	k-ε
Outlet	Pressure outlet	300	310	k-ε

Since the conditions during operation are not known for the steel wall and bottom, they were modeled as solid faces with the material property steel.

2.4. Material Properties

There are three types of materials that data is required in order to model the oven using Fluent. They are the heated air, the insulation, and the steel inside the oven. The Table 2.2 shows the material properties.

Table 2.2: Material properties used in the oven calculations

Material	Density (kg/m ³)	Cp (J/Kg K)	Thermal Conductivity (W/m k)
Air	0.552	1053	0.04395
Insulation	80	1200	0.11
Steel	7801	473	43

2.5. Generation of Mesh

Geometry is created to represent the boundaries and fluid domain for analysis. This geometry is created in 3-D using workbench ICEM 14.5. Once all the critical points are placed, they are joined together by lines to create the edges of the oven geometry (insulation, bottom, inlets and outlets, curves). From these edges and faces are created which represents the fluid domain (air inside the oven). The next step in the creation of the geometry is to generate the mesh on edges and faces. ICEM 14.5 offers many choices with regards to the number of nodes on the edges either by giving the number of nodes or the spacing between the nodes. In this instance, the structured rectangular type of meshing is used to generate mesh. The total numbers of nodes generated are 1472086. Now the generated mesh is converted to unstructured mesh and then 3-D mesh is exported to Fluent.

2.6. Flow Equations

To analyze the air flow inside the oven correctly, the correct model needs to be chosen. Since there is a recirculation of the gases inside the oven due to the fan, turbulent flow is predicted. The models used in Fluent for turbulence are two-equation turbulence models or the Reynolds stress model. The standard two-equation (k-ε) model has been chosen to carry out the analysis on the oven as it is reasonably accurate over a wide range of turbulent flow [6].

2.6.1. Mass Conservation

The conservation of mass or continuity equation is given by:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t} (\rho_{ui}) = 0 \dots \dots \dots 2.1$$

International Journal of Innovative Research in Science, Engineering and Technology

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Website: www.ijirset.com

Vol. 6, Issue 6, June 2017

2.6.2. Momentum Conservation

The conservation of momentum otherwise known as the Navier-Stokes equation which is given by:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \dots \dots \dots 2.2$$

Where p is the static pressure, τ_{ij} is the stress tensor described by equation following equation (2.3). ρg_i is the gravitational body forces and F_i are the external body forces.

The stress tensor " τ_{ij} ", is given by

$$\tau_{ij} = [\mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] - \frac{2}{3}\mu \frac{\partial u_l}{\partial x_l} \delta_{ij} \dots \dots \dots 2.3$$

where μ is the molecular viscosity and δ_{ij} is the effect of volume dilation.

2.6.3. Conservation of Energy

The energy conservation equation is needed to solve for the temperature and the heat transfer which is given by

$$\frac{\partial}{\partial t} (\rho h) + \frac{\partial}{\partial x_i} (\rho u_i h) = \frac{\partial}{\partial x_i} \left[\left(k + \frac{\mu_t}{Pr_t} \right) \frac{\partial T}{\partial x_i} \right] + \frac{Dp}{Dt} + (\tau_{ik})_{eff} \frac{\partial u_i}{\partial x_k} + S_h \dots \dots \dots 2.4$$

Where h is the sensible enthalpy, k is the molecular conductivity, τ_{ik} is the deviatoric stress sensor, μ_t is the turbulent viscosity and Pr_t is the turbulent Prandtl number for temperature or enthalpy.

III. RESULT AND DISCUSSION

The results obtained for the existing boundary condition and geometry modification are explained below.

3.1. Oven at Existing Boundary Condition

The results of CFD analysis of the industrial oven for existing setup are obtained. The boundary conditions at which the analysis is carried out are as shown in the Table 3.1.

Table 3.1: Boundary conditions for existing oven

Boundary Name	Boundary Type	Temperature (°K)	Pressure (Pa)
Inlet_Left	Pressure Inlet	500	150
Inlet_Right	Pressure Inlet	500	141

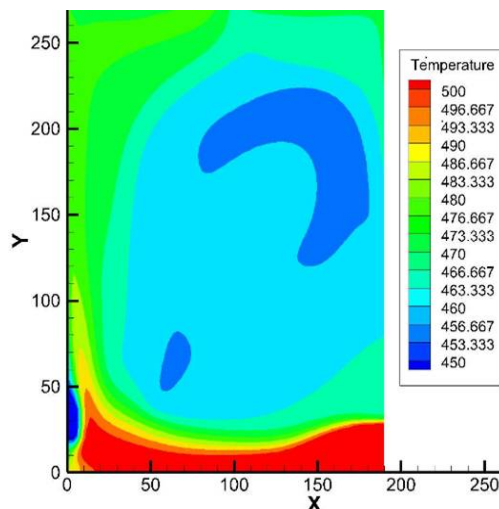


Figure 3.1: Contours of temperature distribution in the oven for existing boundary conditions

From the Figure 3.1, it is observed that the temperature near the bottom of the oven is around 495 °K-500 °K. This is due to the fact that, the inlet slits to the oven are at some height from the bottom, the region is developed where almost

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Vol. 6, Issue 6, June 2017

stagnation condition occurred. The temperature goes on reducing in the upward direction of oven. At the top right corner, the temperature is much lower than the oven surrounding which is 450 °K. The results obtained from the CFD analysis are significantly equivalent to the TTR done prior to the problem identification.

3.2. Effect of Position Variation of Inlet Slit

The boundary conditions at which the analysis is carried out are as shown in Table 3.2.

Table 3.2: Boundary conditions for oven at slit position adjacent to the bottom

Boundary Name	Boundary Type	Temperature (°K)	Pressure (Pa)
Inlet_Left	Pressure Inlet	490	130
Inlet_Right	Pressure Inlet	490	130

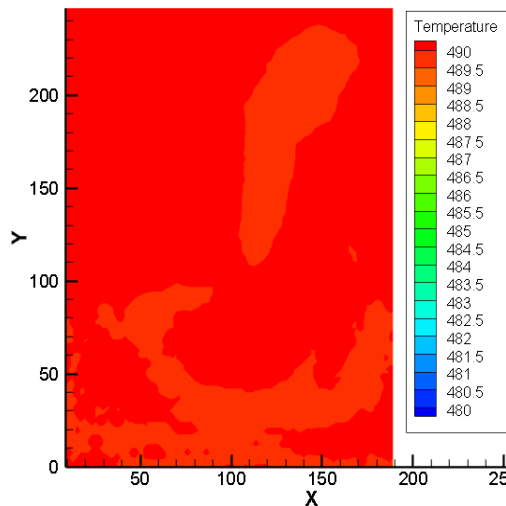


Figure 3.2: Contours of Temperature Distribution for oven at slit position adjacent to the bottom

The results of CFD analysis of the oven by varying the position of Inlet slits adjacent to bottom of oven are obtained. With this geometry modification, the temperature contours obtained from the CFD analysis shows that the temperature inside the oven ranges in between 488°K to 490 °K. which is the specified range of operation. From this it is concluded that maintaining constant pressure on both the left and right inlet with slit inlets adjacent to the bottom, the uniform temperature can be achieved throughout the oven as shown in Figure 3.2

3.3. Effect of Using Perforated Inlet through Bottom of oven

The boundary conditions at which the analysis is carried out are as shown in the Table 3.3.

Table 3.3: Boundary conditions for oven using Perforated Inlet through Bottom

Boundary Name	Boundary Type	Temperature (°K)	Pressure (Pa)
Inlet_Left	Pressure Inlet	480	130
Inlet_Right	Pressure Inlet	480	130

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 6, June 2017

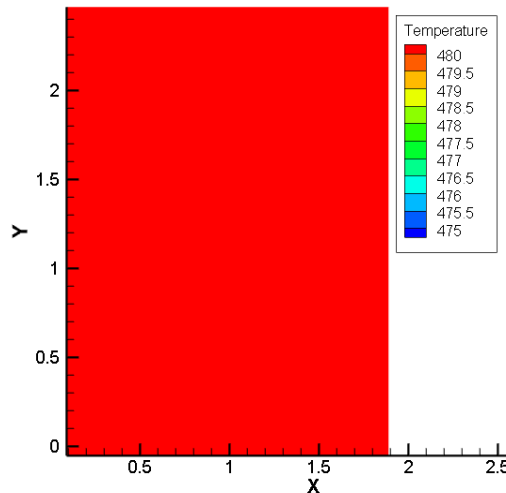


Figure 3.3: Contours of Temperature Distribution through Perforated Inlet

Figure 3.3 shows the CFD analysis for the oven with inlet through the perforated bottom. The temperature contours shows uniform temperature distribution inside the oven. Temperature varies in very narrow range of 488 °K to 490 °K. The distribution of temperature contours is as shown in Figure 3.3.

IV. CONCLUSION

The modeling and analysis of temperature distribution for gas fired convection oven at GUKSS Industries is carried out by using CFD analysis. From the results obtained it is concluded that:

1. At existing shape and boundary condition, there is problem of non uniform temperature distribution in the oven. In particular, the area near bottom of oven is overheated due to the stagnation of hot inlet air. The geometry modification done to achieve uniform temperature distribution in the oven are having air entry to oven through inlet slit adjacent to bottom and using perforated inlet through bottom.
2. From the CFD analysis of modified geometry, the uniform temperature distribution is obtained throughout the oven section. The range of temperature variation is limited to ± 2 °K. This results in considerable saving in both power and time.

<p>Nomenclature</p> <p>q_k Amount of heat transferred by conduction (W)</p> <p>k Thermal conductivity of the medium ($W m^{-1} K^{-1}$)</p> <p>A Area through which the heat is transferred (m^2)</p> <p>$\frac{dT}{dx}$ Temperature gradient normal to the area (K/m)</p> <p>q_c Amount of heat transferred by convection (W)</p> <p>h_c Average convection heat transfer coefficient ($W m^{-2} K^{-1}$)</p> <p>ΔT Temperature Difference $= (T_s - T_\infty)$ (K)</p> <p>g Acceleration due to gravity ($m s^{-2}$)</p> <p>β Coefficient of expansion (K^{-1})</p> <p>L Characteristic length (m)</p> <p>ν Kinematic Viscosity ($m^2 s^{-1}$)</p> <p>P_r Prandtl Number (-)</p> <p>Nu Nusselt Number (-)</p>	<p>ρ Density ($Kg m^{-3}$)</p> <p>G_r Grashof Number (-)</p> <p>μ Dynamic Viscosity ($Kg m^{-1} s^{-1}$)</p> <p>C_p Specific Heat at Constant Pressure ($J Kg^{-1} K^{-1}$)</p> <p>α Thermal Diffusivity ($m^2 s^{-1}$)</p> <p>p Static pressure (N/m^2)</p> <p>τ_{ij} Stress tensor ($N m^{-2}$)</p> <p>ρ_{gi} Gravitational body forces (N)</p> <p>F_i External body forces (N)</p> <p>h Sensible enthalpy (J)</p> <p>τ_{ik} Deviatoric stress tensor ($N m^{-2}$)</p> <p>Pr_t Turbulent Prandtl number for temperature. (-)</p> <p>μ_t Turbulent Viscosity ($Kg m^{-1} s^{-1}$)</p> <p>τ Shear Stress ($N m^{-2}$)</p>
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Vol. 6, Issue 6, June 2017

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