DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER AND FLUID FLOW ANALYSES OF DOMESTIC OVENS

by
İhsan Doruk ÜNSALAN

January, 2014
İZMİR

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER AND FLUID FLOW ANALYSES OF DOMESTIC OVENS

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in Mechanical Engineering, Energy Program

by
İhsan Doruk ÜNSALAN

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER AND FLUID FLOW ANALYSES OF DOMESTIC OVENS"** completed by **İHSAN DORUK ÜNSALAN** under supervision of **PROF. DR. DİLEK KUMLUTAŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER AND FLUID FLOW ANALYSES OF DOMESTIC OVENS

ABSTRACT

The aim of this study is to investigate the heat transfer and fluid flow mechanics of domestic ovens which are used commonly at households, using numerical and experimental methods. Thus, interior air volume of a domestic oven and this oven's upper fan unit were modeled using the Computational Fluid Dynamic and Heat Transfer (CFDHT) method and analyses were made. The numerical results were validated by comparing with the results obtained from the experimental study. Both steady state and transient analysis have been completed for the investigations. To simulate the real working conditions of the oven an external FORTRAN code has been used in the transient analysis. So, it was possible to predict the temperature and flow distributions in the oven cavity. The success of this study is to develop an investigation method of heat transfer and fluid flow characteristics for domestic ovens.

Keywords: Domestic ovens, computational fluid dynamics and heat transfer.

EV TİPİ FIRINLARIN ISI TRANSFERİ VE AKIŞ ANALİZLERİNİN SAYISAL VE DENEYSEL İNCELENMESİ

ÖZ

Bu çalışmanın amacı evlerde sıklıkla kullanılan ev tipi fırınların ısı transferi ve akış karakteristiklerinin sayısal ve deneysel yöntemler kullanılarak incelenmesidir. Bunun için, ev tipi fırın ve bu fırının üzerindeki fan kanalı için iç hava hacimleri, Hesaplamalı Akışkanlar Dinamiği ve Isı Transferi (HADIT) kullanılarak modellenmiş ve analizler gerçekleştirilmiştir. Sayısal sonuçlar deneysel çalışmadan elde edilen sonuçlar kullanılarak doğrulanmıştır. İncelemelerde kararlı rejim ve zamana bağlı analizler kullanılmıştır. Fırın gerçek çalışma şartının benzetimi için program dışı çalışan bir FORTRAN kodu kullanılmıştır. Böylece, fırın içindeki sıcaklık ve akış dağılımları tahmin edilebilmiştir. Bu çalışmanın başarısı ev tipi fırınların ısı ve akış transferi karakteristiklerini inceleyecek bir yöntem geliştirmesidir.

Anahtar kelimeler: Ev tipi fırınlar, hesaplamalı akışkanlar dinamiği ve ısı transferi.

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CHAPTER ONE
INTRODUCTION

1.1 Literature Survey

The aim of this study is to investigate the heat transfer and fluid flow characteristics of domestic ovens which are commonly used in households by conducting steady state and transient analyses and validate the numerical results with the data obtained from the experimental study.

A prototype pyrolytic domestic oven has been usedin this study. Pyrolytic function is a self-cleaning method used in domestic ovens. This method uses very high temperatures (more than 500 °C) over long (1-3 hours) cycles, in order to incinerate the organic residues that are then can be easily removed as dust. This method is currently the main commercial solution on the market as pointed out in the study of Palmisano, Hernandez, Hussain, Fino & Russo (2011).

In the study of Verboven, Scheerlinck, Baerdemaeker & Nicolai (2000a), they have investigated the forced convection in an oven using CFD methods. They have compared the numerical results of their study with experimental results of the oven. The heaters and fan of the oven of their study has not been modeled to reduce the computing cost for the analysis. The oven of this study has different airflow inlets than the typical ovens which are located at the sides of the oven. The heat transfer coefficients in this study have been computed more accurately by using turbulent boundary layer approach around the walls of the oven.

In another study of Verboven, Scheerlinck, Baerdemaeker & Nicolai (2000b), they have investigated forced convection using the isothermal air flow. They have neglected the differences of the air inside the oven cavity while preparing the numerical model. In this study, RNG k-ε turbulence model has been used instead of k-ε turbulence model. A model consisting of 55944 elements have been used. In this study, an approximately of 22 % mean difference have been found between the

numerical study for the air flow results. The schematic representation of the electrical forced convection oven of this study is shown in Figure 1.1.

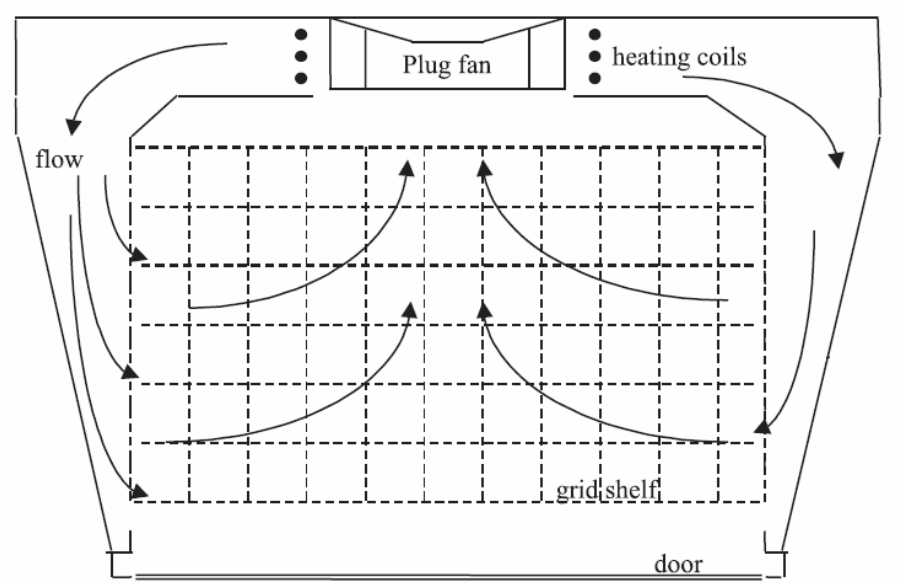


Figure 1.1 Electrical forced convection oven (Verboven, Scheerlinck, Baerdemaeker & Nicolai, 2000b).

In the study of Smolka, Nowak & Rybarz (2009), they have investigated the forced convection inside a drying oven by using experimentally validated 3-D CFD analysis. The oven of this study used at a constant, spatially uniform temperature. To improve temperature uniformity within the oven cavity, they have changed the parameters such as the rotational speed of the device fan, the effectiveness of the distribution gaps and the rate of heat generated in the electrical heaters. They have also changed the configurations such as the locations of the heaters, the fan and the fan baffle. By completing these processes, they have improved the temperature uniformity and validated the results with the experimental test of the modified prototype.

In the study of Mistry, Ganapathisubbu, Dey, Bishnoi & Castillo (2011), they have developed a CFD based methodology to evaluate performance of a domestic oven. This involves modeling three-dimensional, unsteady, forced convective flow field coupled with radioactive participating media. The gas oven of this study is shown in Figure 1.2.

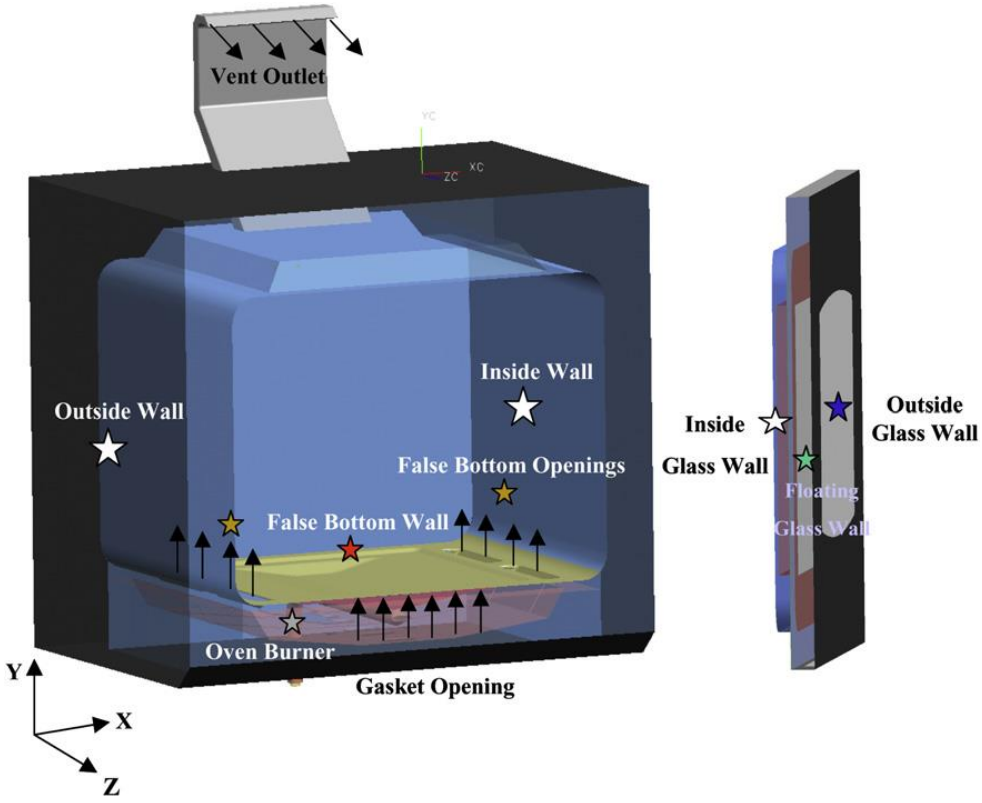


Figure 1.2 The gas oven (Mistry, Ganapathisubbu, Dey, Bishnoi& Castillo, 2011).

For capturing transient heat transfer coupled with mixed convection flow field are evaluated considering the trade-off between computational time and accuracy of predictions. The results of this study showed 6% discrepancy with experimental data.

CHAPTER TWO
NUMERICAL STUDY

2.1 Introduction of Numerical Study

The domestic oven used in this study has been investigated with a three stage process. These stages are as follows:

- Steady state isothermal analysis of the oven's upper fan unit.
- Steady state thermal analysis of the oven cavity.
- Transient thermal analysis of the oven cavity.

The first analysis of this study is concerned with the oven's upper fan unit which is shown in Figure 2.1. As seen from the Figure 2.1, the upper fan unit of the oven has been created as half model for simplification reasons since the air flow in the unit has been considered as symmetrical. The oven which is investigated in this study has a chimney above the oven cavity. The model of the oven cavity and the chimney area has been shown respectively in the Figure 2.2, Figure 2.3. The purpose of this analysis is to acquire the necessary output data of the chimney of the oven cavity which is required for the remaining analyses.

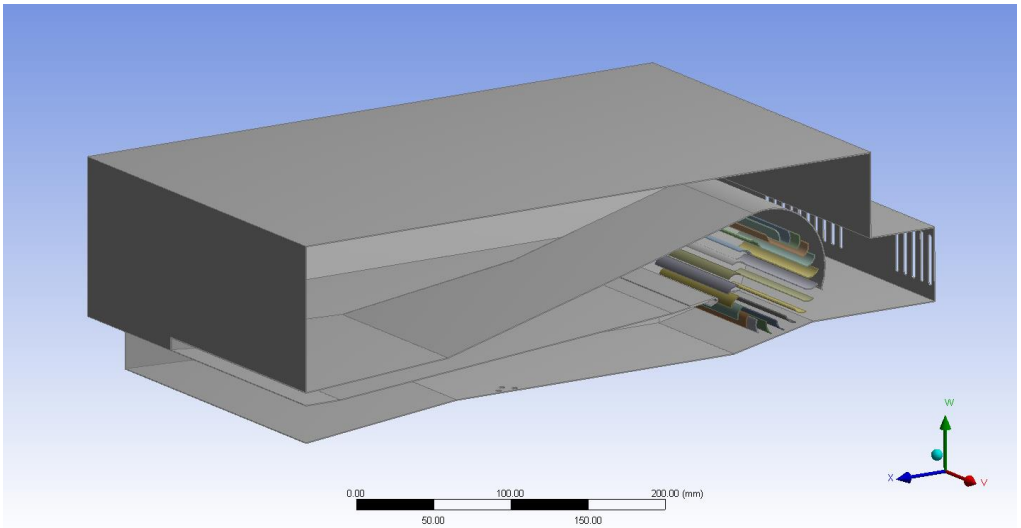


Figure 2.1The upper fan unit of the oven.

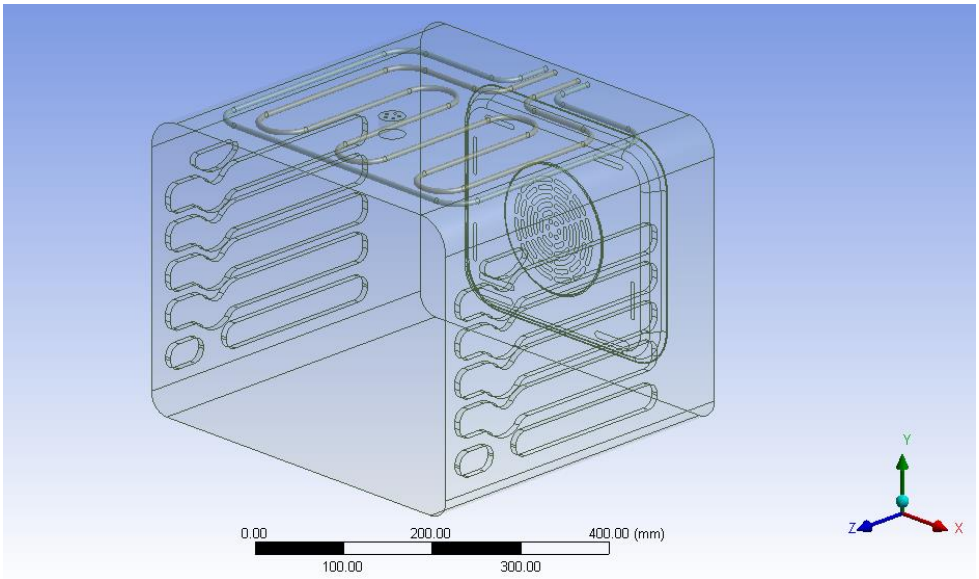


Figure 2.2 The model of the oven cavity.

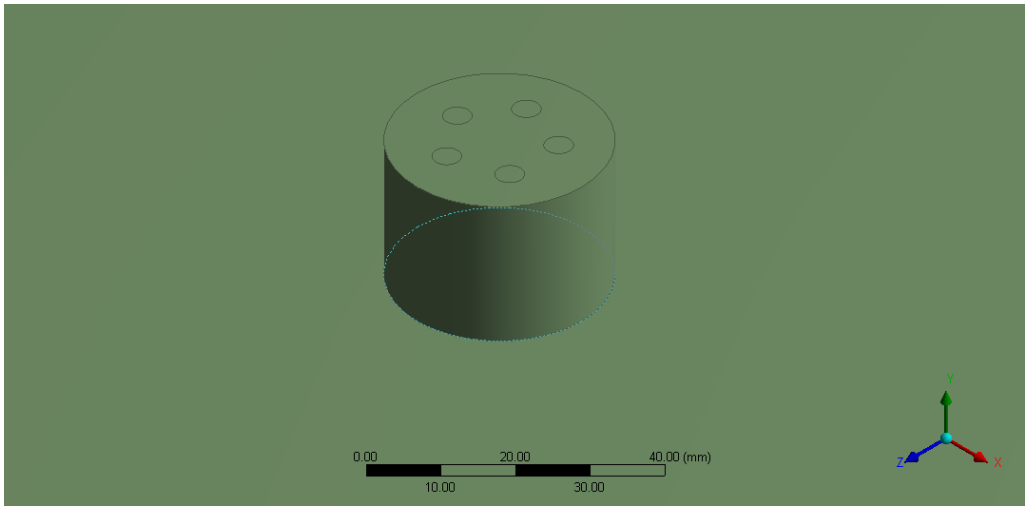


Figure 2.3 The chimney of the oven cavity.

The second analysis of this study is the steady state thermal analysis of the oven cavity. This analysis has been solely made for the purpose of comparing with the transient thermal analysis of the oven cavity. Since the oven in this study is controlled with a thermostat to operate within a preset temperature range, the oven's operating process should be considered as transient. Therefore the transient analysis is more important for accurately modeling the oven's operation. But, the steady state analysis of the oven cavity can be used as a comparison tool to point out the

inadequate aspects of the steady state approach and is important in this study for this purpose.

The third and final analysis of this study is the transient thermal analysis of the oven cavity. Both of the previously mentioned analyses are made either for the purpose of preparing or comparing with the transient analysis. Although it should be mentioned that the results steady state analysis of the oven's upper fan unit is also used as input for the steady state thermal analysis of the oven cavity.

2.2 The Steady State Analysis of the Oven's Upper Fan Unit

The steps of the analysis of the oven's upper fan unit are as follows:

- Preparing the cad model of the upper fan unit.
- Meshing of the upper fan unit.
- Boundary conditions of the upper fan unit.
- Solver of the upper fan unit.

2.2.1 Preparing the Cad Model of the Upper Fan Unit

The cad model of the oven has been taken from a white goods company for the numerical study. The main purpose of this unit is to actively cooling the oven's door by drawing the air between the oven's glasses. The task is achieved with the fan of the unit.

Another purpose of the fan of this unit is drawing the air from the oven cavity through the chimney of the cavity. Though, the required chimney output data could not be retrieved from the experimental study and thus the purpose of this unit's analysis is to compute the necessary data as has been mentioned before.

The air volume of the unit has been prepared with a modeling program according to the cad model of the oven with necessary assumptions and has been shown in Figure 2.4.

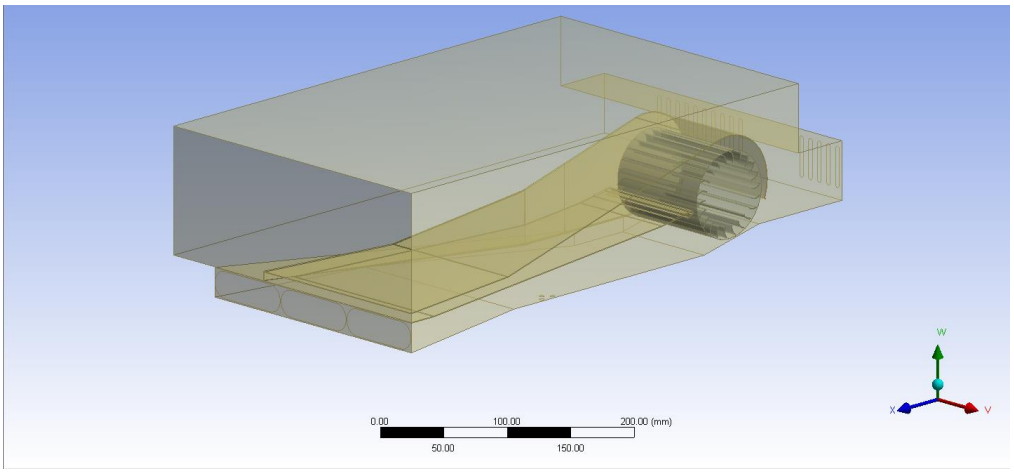


Figure 2.4 The model of the upper fan unit's air volume.

The fan of this unit and the air volume in the rest of the whole unit has been modeled as two bodies. The reason for this is to separate the fan which is a rotating component of the system from the rest of the unit by slicing the area around the fan of the unit. These two bodies are shown respectively in Figure 2.5 and Figure 2.6.

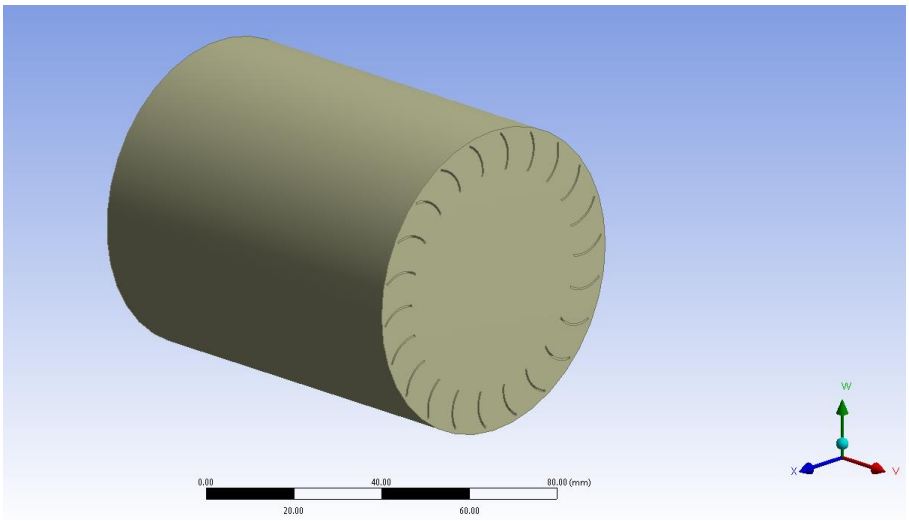


Figure 2.5 The body of the air volume of the unit's fan.

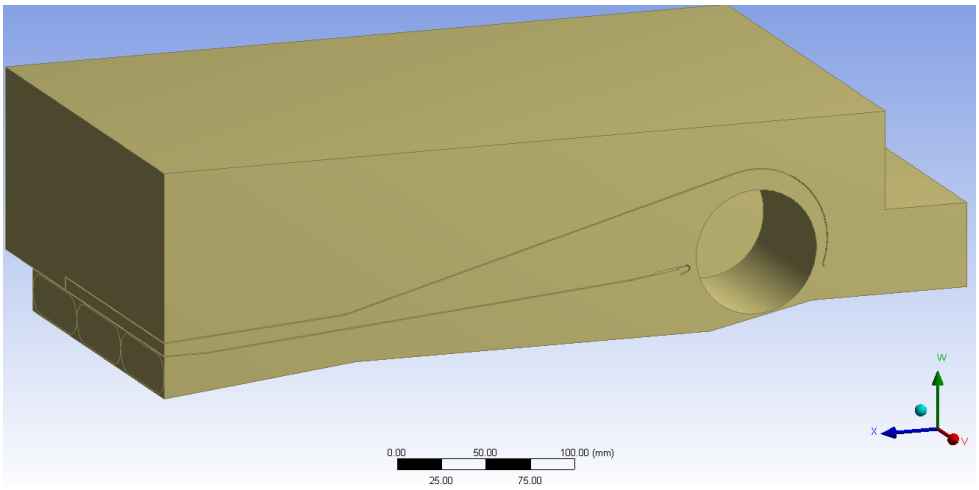


Figure 2.6 The body of the air volume of the rest of the unit.

2.2.2 Meshing of the Upper Fan Unit

The meshing process is the second and arguably the most important step of any Computational Fluid Dynamics (CFD) study after generating the cad model. Because, generating a high quality mesh for the model is a necessity to reach the closest results possibly for the real life operating condition of the system which is being analyzed.

The generated cad model for the upper fan unit of the oven is imported to the package program's mesh module. Necessary named selections for the required faces of the unit which is useful for setting the boundary conditions has been selected before the meshing process.

As the geometry of the unit has been created as two bodies, these bodies also have been meshed with different settings. While the body of the air volume of the unit's fan has been meshed with a body sizing option, the body of the air volume of the rest of the unit has been meshed normally. The reason for selecting a different method for meshing the body of the fan was to accurately capture the rotation movement of the fan. Both mesh structures of the whole unit and the fan of the unit were shown respectively in Figure 2.7 and Figure 2.8.

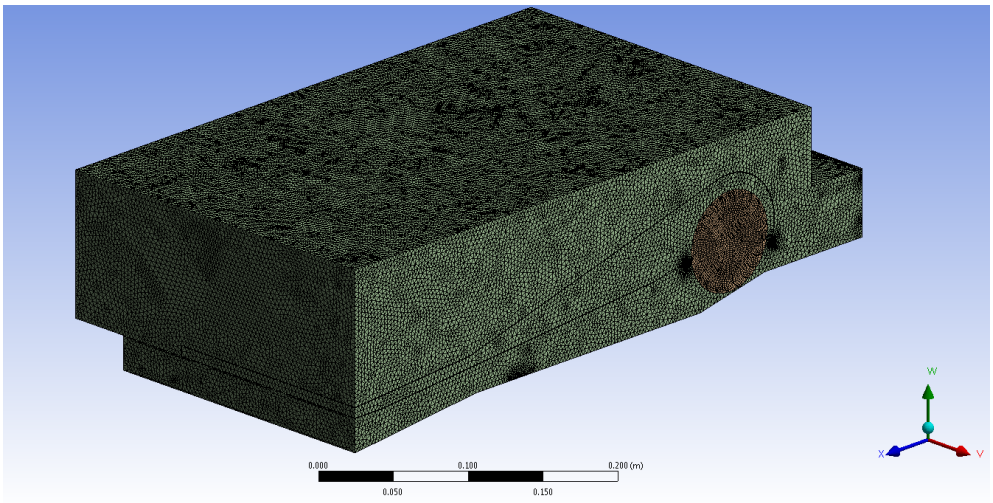


Figure 2.7 The mesh structure of the air volume of the unit.

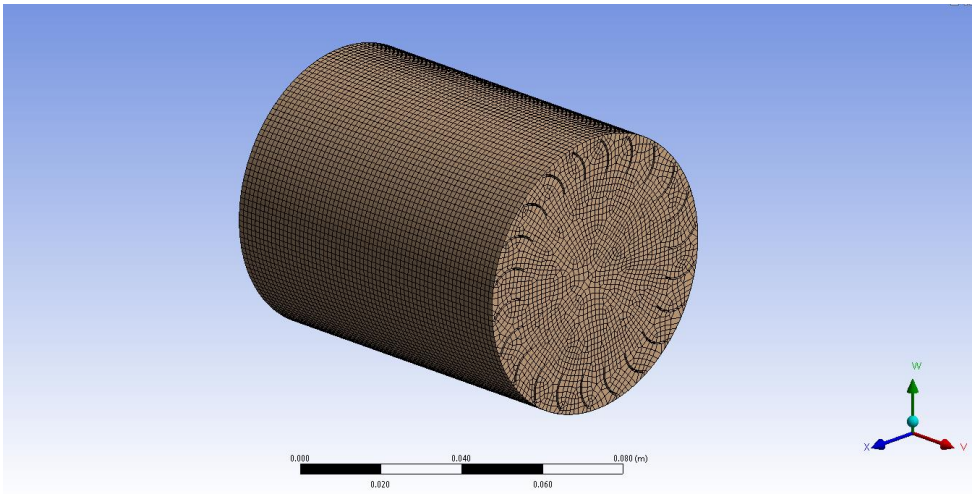


Figure 2.8 The mesh structure of the fan of the unit.

A mesh independency study has been done to determine the optimum mesh for this analysis. Meshes with 733226, 2019884 and 4182954 elements have been created. Preliminary analyses made with these meshes have shown that the mesh with 2019884 is optimum for this analysis and therefore selected. The mesh composed of tetrahedral elements and 512804 nodes.

2.2.3 Boundary Conditions of the Upper Fan Unit

After preparing the mesh, the prepared numerical model of the upper fan unit has been transferred to the CFD program's pre-processor module for setting up the boundary conditions.

Since the model has been created as two bodies, the numerical model has two fluid (air) domains. These two domains which are named as air and fan domains for simplicity is connected to each other with a fluid to fluid domain interface option. Rotating domain motion with angular velocity has been selected for the fan domain. The air domain has been selected as stationary.

All of the faces in which the air flows in or out of the upper fan unit have been selected as openings. That is to say, only the rotating movement of the unit's fan forces the air flow in the whole unit. Symmetry planes of the two bodies have also set at the required faces. Remaining faces which are not openings or symmetry planes have been selected as no slip walls.

Since the changes in angular velocity of the fan are irrelevant in real fan's rotation, the analysis has been made with steady-state assumption. Also, isothermal heat transfer mechanism was chosen, since only the required chimney air flow outlet data is needed to be calculated.

2.2.4 Solver of the Upper Fan Unit

After determining the boundary conditions and setting up the initial conditions, solver control definitions have been made with the program's solver module. The analysis has been completed in 3344 iterations and residuals for the analysis have been shown in Figure 2.10, 2.11.

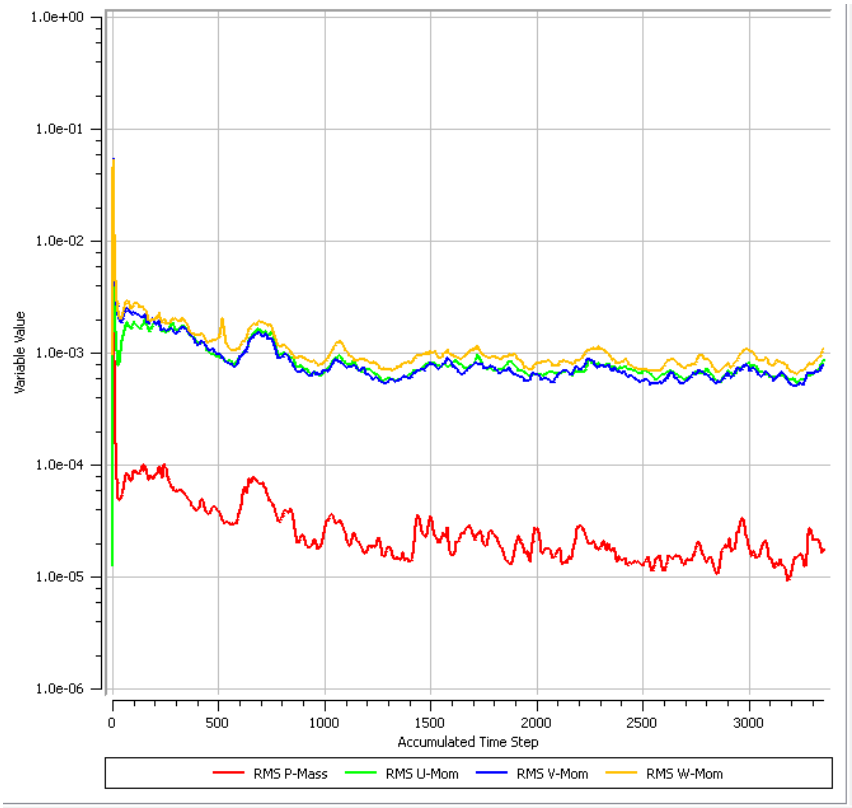


Figure 2.9 Momentum and mass residuals.

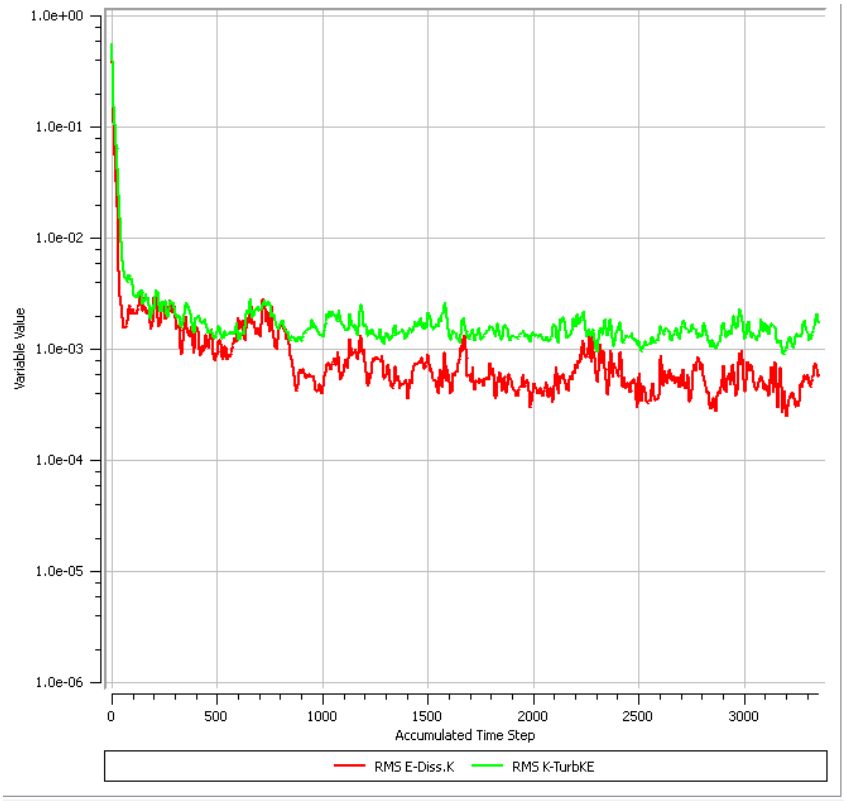


Figure 2.10 Turbulence residuals.

2.3 The Steady State Analysis of the Oven Cavity

The steps of the analysis of the oven cavity are as follows:

- Preparing the cad model of the oven cavity.
- Meshing of the oven cavity.
- Boundary conditions for the steady state analysis of the oven cavity.
- Solver for the steady state analysis of the oven cavity.

2.3.1 Preparing the Cad Model of the Oven Cavity

Even though the oven has four heaters, only the two of them have been modeled for this analysis. Since two of the remaining heaters are not operational during the pyrolytic function of the oven. The heaters have been modeled as two bodies for the boundary condition purposes. Modeled heaters are shown in Figure 2.11.

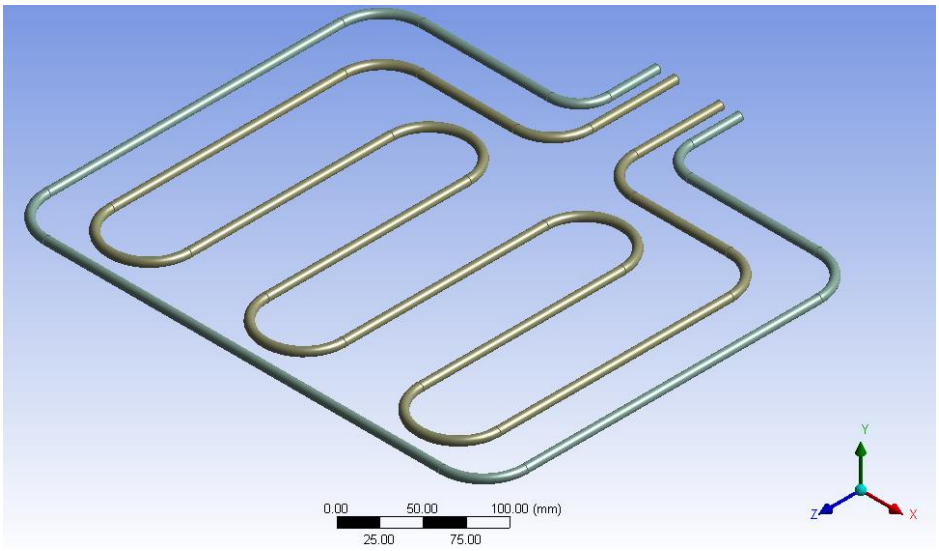


Figure 2.11 Modeled heaters of the oven.

The air volume of the oven has been prepared similarly like the model of the upper fan unit's air volume according to the cad model of the oven with necessary assumptions and has been shown in Figure 2.2. The only difference is two heater bodies which are generated as solid bodies. The model of the oven has been used in

both steady state and transient thermal analyses. Since the only difference between these analyses are the boundary conditions.

The oven has a four-glass door. But for simplicity reasons, oven door has not been modeled. Because, detailed analysis of the oven's door is out of scope of this study. Instead, a preliminary study has been made to obtain the necessary boundary conditions data of the oven door.

The oven also has a turbo fan which is not included in the cad model. Because, rotating movement of the turbo fan presents a great difficulty in transient approach. The transient movement of the turbo fan needs to be captured with very small time steps to achieve a high quality calculation which is not the case for this study. Since, the transient analysis of this study concerns with the thermostatic cycles of the oven's pyrolytic functions, which require bigger time steps. Even though the turbo fan has not been modeled, the effect of the fan simulated with the boundary conditions of the holes around the turbo fan case. This case is shown in Figure 2.12.

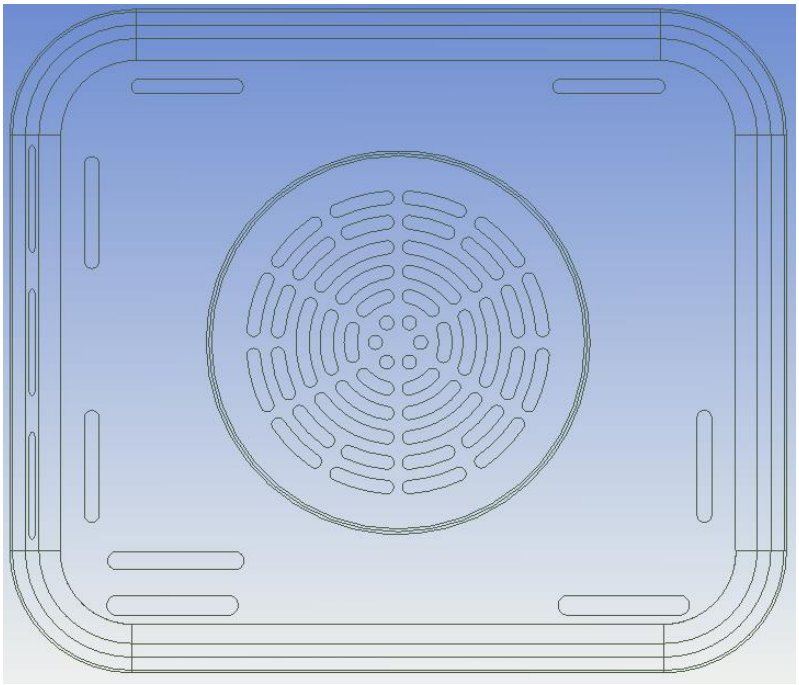


Figure 2.12 The case around the turbo fan.

2.3.2 Meshing of the Oven Cavity

The generated cad model of the oven cavity is imported to the program's mesh module. Necessary named selections for the required faces of the unit which is useful for setting the boundary conditions has been selected before the meshing process.

As the two heaters of the oven have been modeled as bodies, the geometry of the oven consists of three bodies. Mesh structures of the oven and heaters are shown in Figure 2.13 and 2.14.

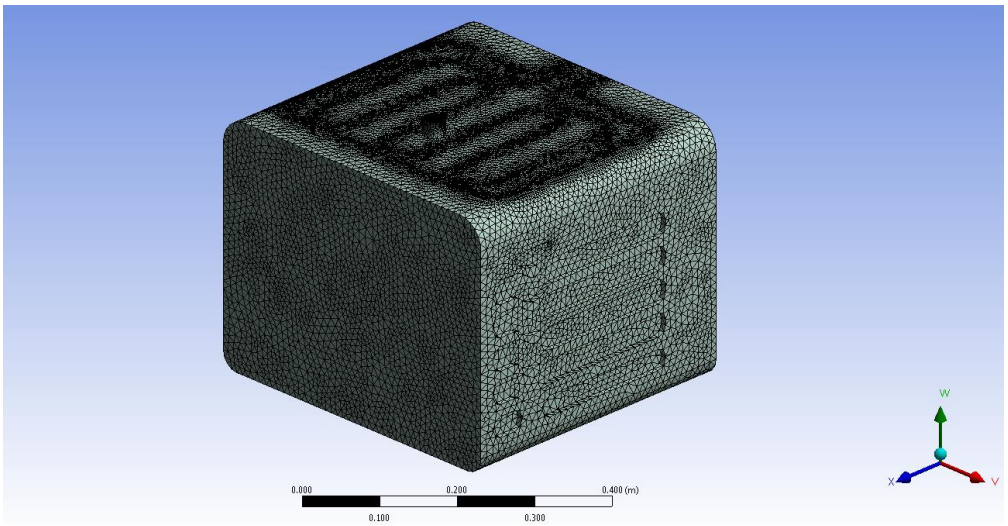


Figure 2.13 The mesh structure of the oven.

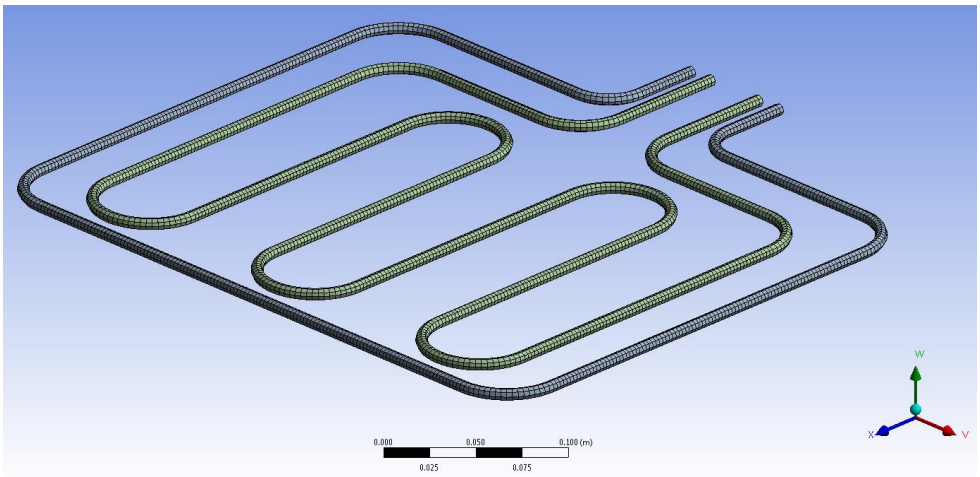


Figure 2.14 The mesh structures of the heaters.

Another mesh independency study has been done to determine the optimum mesh for the oven analyses. Meshes with 667377, 1143630, 2667500 and 8569507 elements have been created. Preliminary analyses made with these meshes have shown that the mesh with 1143630 is optimum for the analyses and therefore selected. The mesh composed of tetrahedral elements and 224556 nodes.

2.3.3 Boundary Conditions of the Steady State Analysis of the Oven Cavity

After generating the mesh, the prepared numerical model of the oven cavity has been transferred to the program's preprocessing module for setting up the boundary conditions.

The prepared bodies of the heaters of the oven have been selected as solid domains. As a result, two fluid-solid interfaces have been defined between these two bodies and the air volume of the oven cavity. Conservative interface flux heat transfer has been selected for these interfaces. To define the heat flux into the oven cavity, two sub domains have been created in these domains. Heat source then defined as volumetric flux, according to the power of the respective heaters and their volumes.

In the study of Mistry, Ganapathisubbu, Dey & Castillo (2006), discrete transfer surface to surface radiation option has been used. This approach has also been used in this study to simulate the radiation heat transfer in the oven. Thermal emissivity coefficients which were obtained from the white goods company has been defined to all of the required faces and interfaces for this purpose.

The holes around the turbo fan have been numbered for the ease of setting the air flow inlet into the oven cavity which is shown in Figure 2.15. Since the fan of the unit has not been modeled, opening surfaces has been selected at the required faces of the case. Opening option has been chosen because of the purpose of mass conservation. The mean temperature of the air flow through the opening surfaces has

been calculated and set as the air flow inlet's temperature. The air flow inlets through the holes around the case of the turbo fan are shown in Table 2.1.

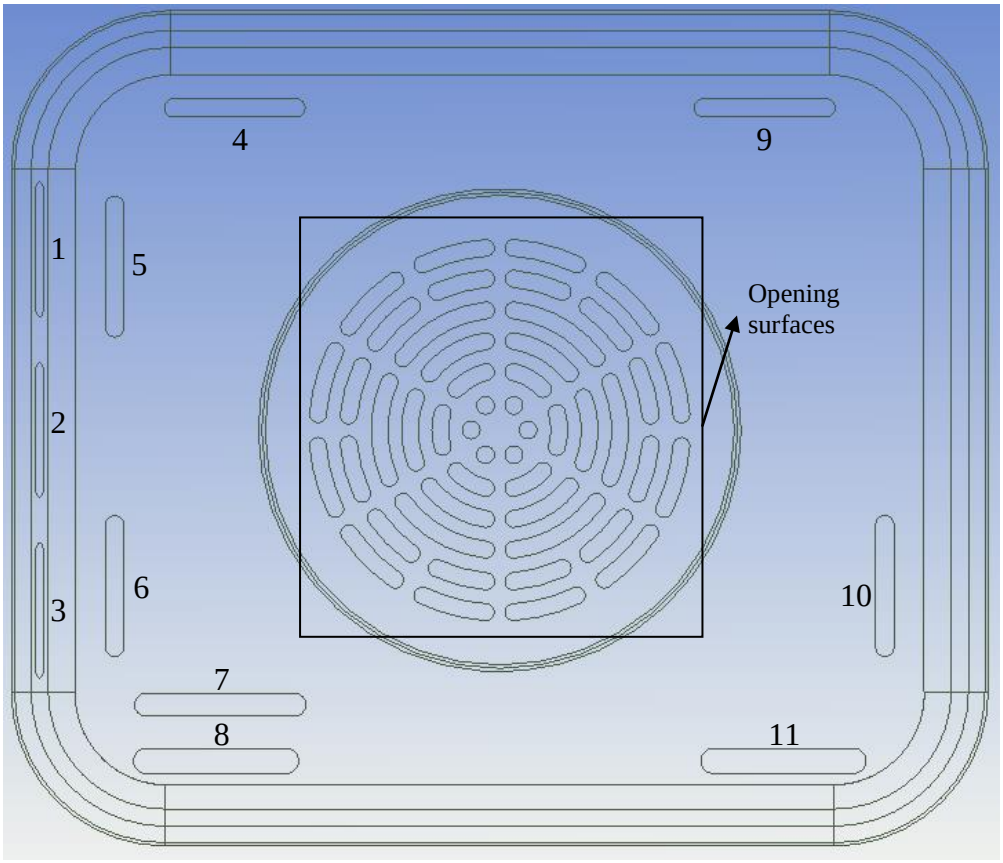


Figure 2.15 The numbered inlets and opening surfaces of the turbo fan case.

Table 2.1 Air flow inlets of the holes around the case of the turbo fan.

Inlet	Mass Flow (kg/s)
1	0.001796
2	0.000837
3	0.001510
4	0.001301
5	0.002023
6	0.000740
7	0.003141
8	0.003361
9	0.002045
10	0.002241
11	0.001037

Covering of the oven walls consist of sheet metal, aluminum foil, insulation material and sheet metal from inside to outside. Overall heat transfer coefficient for the walls of the oven has been calculated based on the thermal resistances and assuming average temperatures of external walls. While calculating these coefficients, only the insulation material's thermal resistance has been considered. Rest of the materials' thickness was determined irrelevant for the coefficient. Overall heat transfer coefficient (U, W/m^2) was calculated by (Incropera, DeWitt, Bergman & Lavine, 2006, p.100);

$$U = \frac{1}{l_y/k_y} \tag{2.1}$$

In Equation 2.1, l_y (m) is the thickness of the insulation material and k_y (W/mK) is the thermal conductivity of the insulation material.

Determined boundary conditions of the oven walls and door according to the experiments and assumptions are shown in Table 2.2.

Table 2.2 Overall heat transfer coefficients of the oven walls and door.

Region	Overall Heat Transfer Coefficient (U, W/m^2K)
Left Wall	1.165
Top Wall	1.165
Right Wall	1.165
Bottom Wall	1.165
Back wall	1.165
Oven Door	16.002

2.3.4 Solver of the Steady State Analysis of the Oven Cavity

After determining the boundary conditions and setting up the initial conditions, solver control definitions have been made with the program's solver module. The analysis has been completed in 8275 iterations, residuals and selected monitor points for the analysis are shown in Figure 2.16, 2.17, 2.18, 2.19 and 2.20.

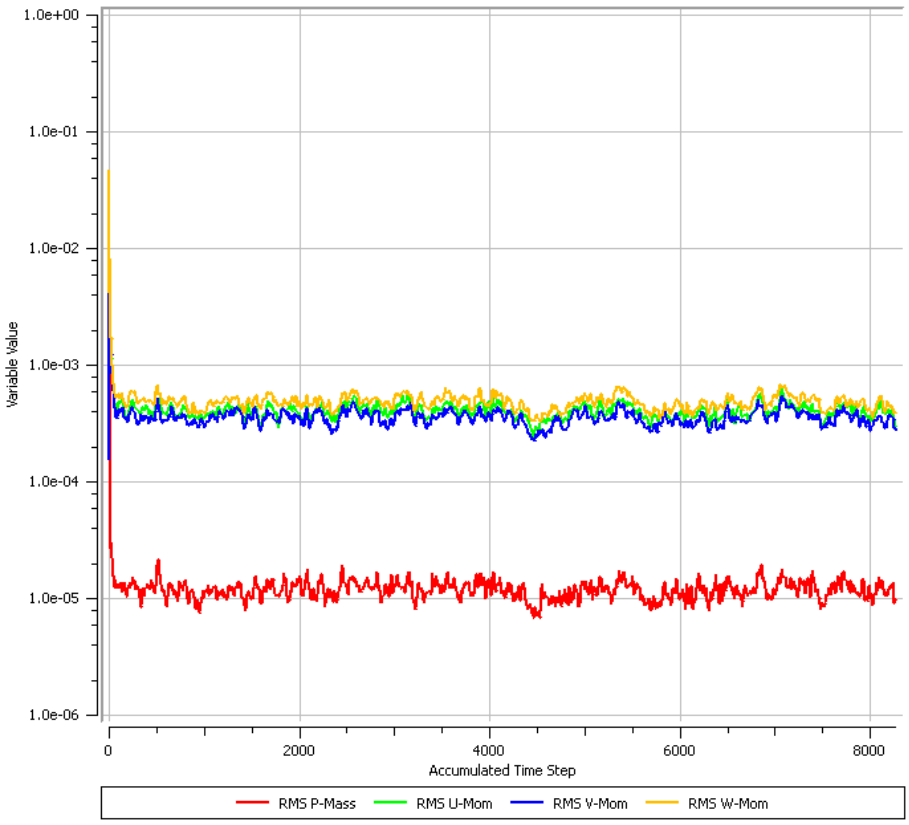


Figure 2.16 Momentum and mass residuals of the steady state analysis of the oven cavity.

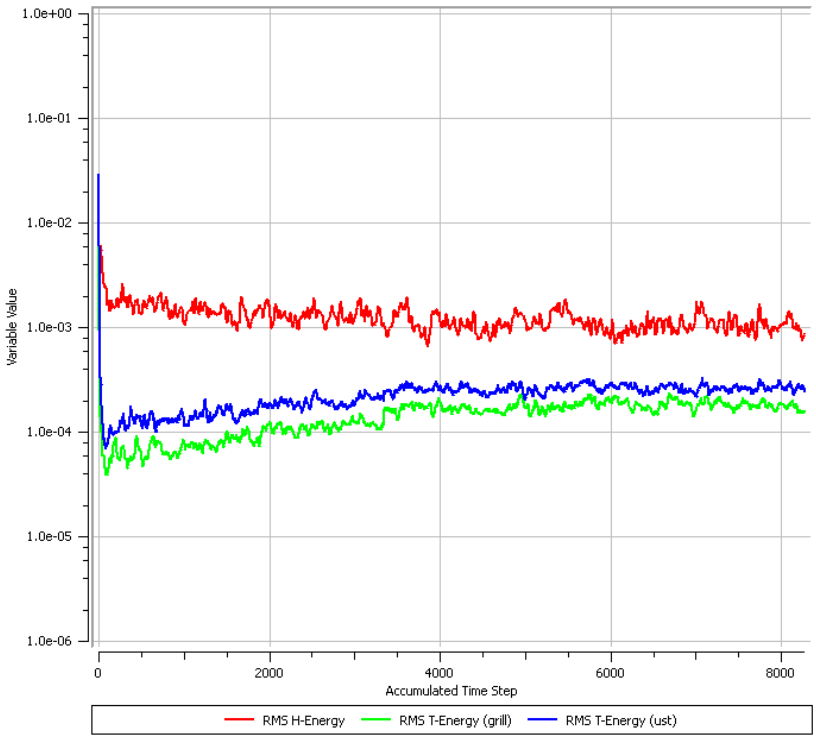


Figure 2.17 Heat transfer residuals of the steady state analysis of the oven cavity.

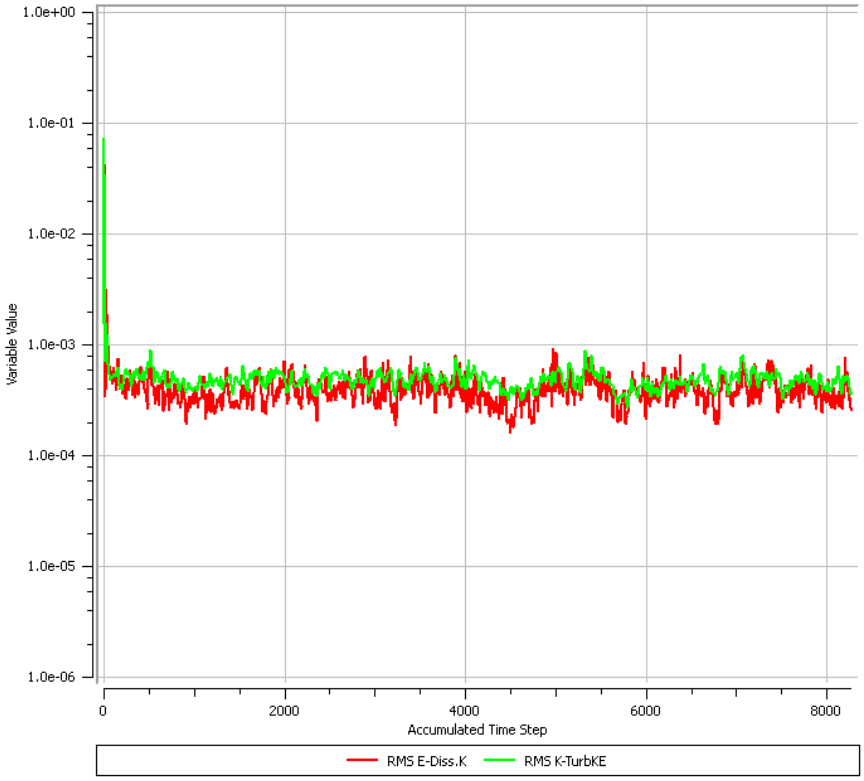


Figure 2.18 Turbulence residuals of the steady state analysis of the oven cavity.

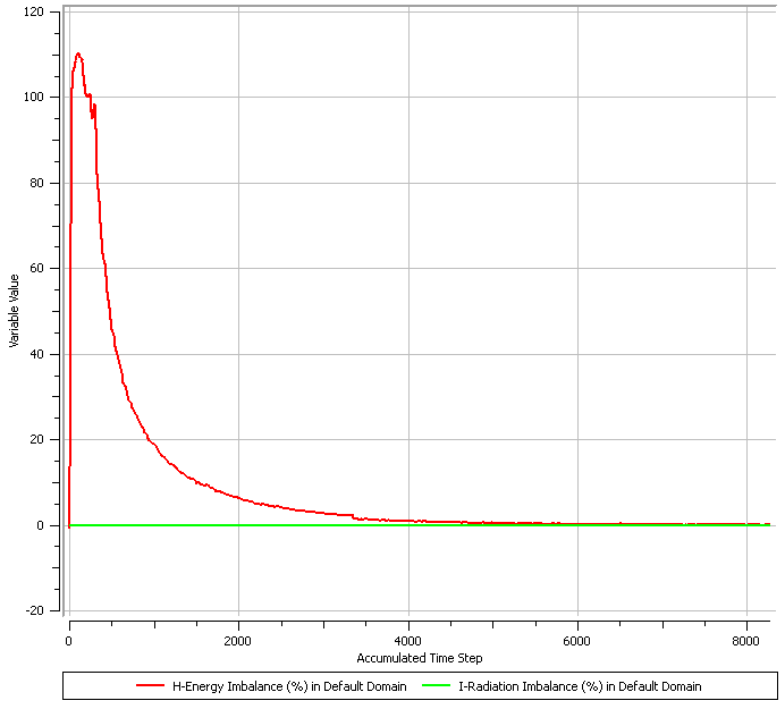


Figure 2.19 Domain imbalances of the steady state analysis of the oven cavity.

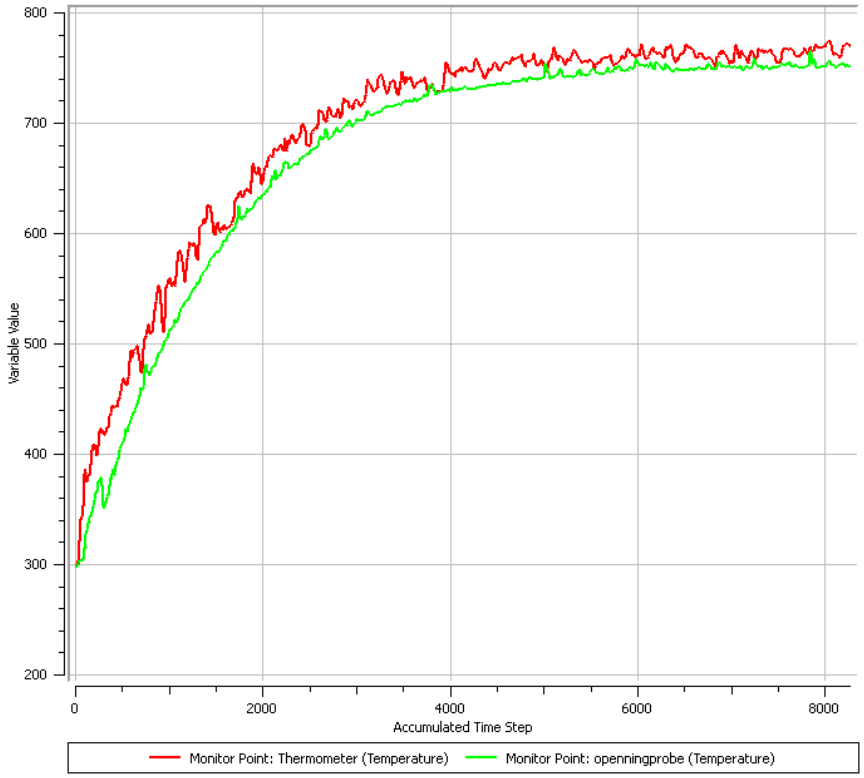


Figure 2.20 Temperatures at the selected monitor points of the steady state analysis of the oven cavity.

In Figure 2.20, two previously selected monitor points have been shown. The Monitor point "Thermometer" represents the thermometer probe located at the position of the oven's thermostat while monitor point "openingprobe" represents the thermometer probe located near the opening surfaces' of the oven cavity.

2.4 The Transient Analysis of the Oven Cavity

The steps of the transient analysis of the oven cavity are as follows:

- Boundary conditions of the transient analysis of the oven cavity.
- Solver of the transient analysis of the oven cavity.

Both preparing the cad model of the oven cavity and meshing of the oven cavity has been skipped since both of these two steps are same for these analyses.

2.4.1 Boundary Conditions of the Transient Analysis of the Oven Cavity

Boundary conditions of the transient analysis of the oven cavity are mostly the same as the state analysis of the oven cavity. The only difference between these two analyses is the analysis type and thermostat (on/off) control of the oven.

In the similar study of Mistry, Ganapathisubbu, Dey, Bishnoi& Castillo (2011), they used 10s time steps for their oven's analysis. In this study these time steps has also been used. For the purpose of developing the air flow in the oven cavity, 0.5s preliminary time steps have been used. Every time step has analyzed with 3 iterations.

The domestic oven analysis is a transient problem by the reason of the thermostat on-off cycle that occurs the oscillating of temperatures of the internal air volume of the oven. When the oven sets to an operating function and starts, the oven heats to a preset temperature until the thermostat shuts off the heaters. The oven then starts to cool down to a selected temperature and when that temperature is reached; the thermostat starts the heaters again. These cycles go on for the duration of the selected function. For simulating the thermostat control of the oven; a FORTRAN code has been used.

2.4.1.1 FORTRAN Code of the Transient Analysis of the Oven Cavity

The prepared FORTRAN code for the transient analysis has been processed with the programs preprocessing module as to obtain necessary files for the code to operate with program. After that a sub routine for the code has been selected, since this is needed by the program to call and locate the code. Then, a function has been created as to setup the argument units between the code and the program.

Three of the four of the argument units are temperatures. These temperatures are preset maximum temperature of the oven, temperature tolerance and temperature at

the location of the thermostat probe. The last argument unit is a 1-0 response of the code which is needed for the analysis.

The heat flow of the heaters has been defined as a user function to operate cooperatively with the program. When the analysis starts, the code also starts to check the temperature from the thermostat probe after every time step. When the preset temperature exceeds at any time the code send responses the program and causes to shutting down of the heaters. Then, oven starts to lose the heat and cools down until the tolerance temperature has been exceeded. The code then, causes the heaters to start again. These cycles continue until the end of the analysis.

2.4.2 Solver of the Transient Analysis of the Oven's Cavity

After determining the boundary conditions and setting up the initial conditions, solver control definitions have been made with the program's solver module. The analysis has been completed in 450 time steps. Residuals for the analysis have been shown in Figure 2.21, 2.22 and 2.23.

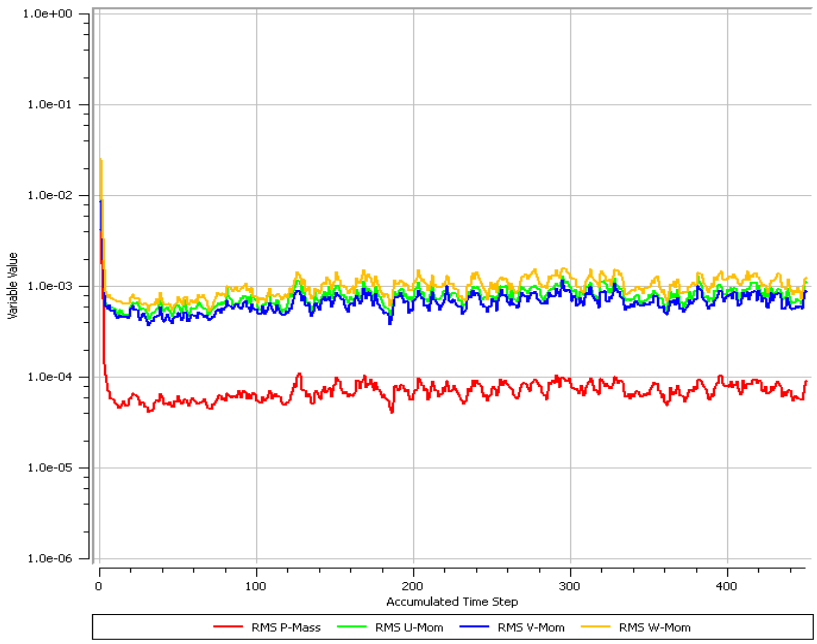


Figure 2.21 Momentum and mass residuals of the transient analysis of the oven cavity.

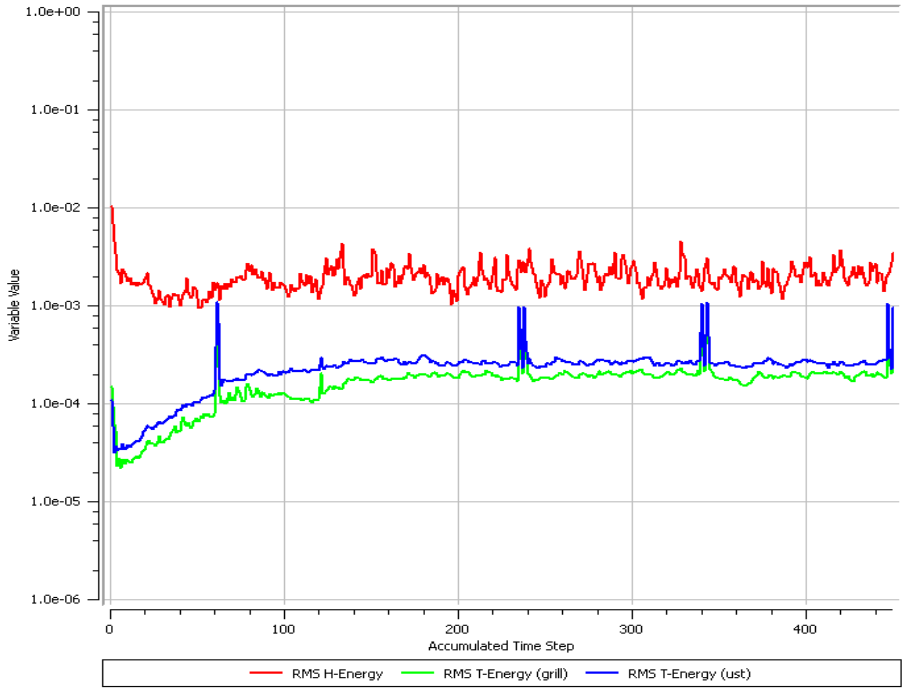


Figure 2.22 Heat transfer residuals of the transient analysis of the oven cavity.

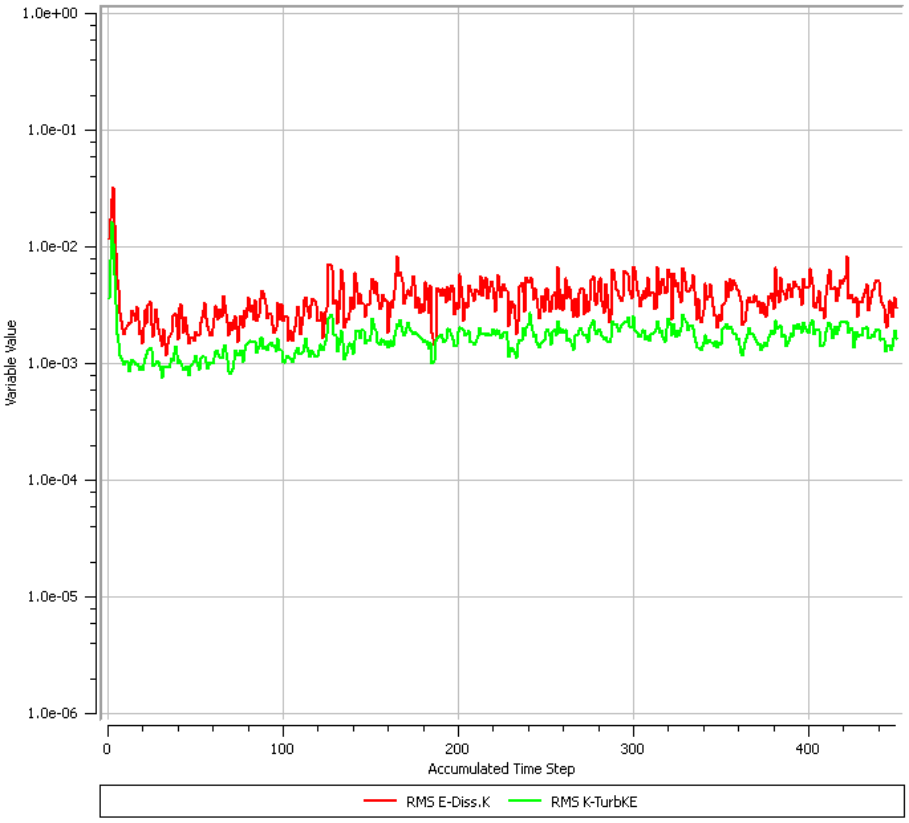


Figure 2.23 Turbulence residuals of the transient analysis of the oven cavity.

CHAPTER THREE
EXPERIMENTAL STUDY

In the previous chapter, CFD analyses of the upper fan unit and the oven cavity have been completed. In this chapter, the accuracy of the numerical results of those analyses will be confirmed by compared with the results of the experimental study.

3.1 Experimental Study of the Upper Fan Unit

In the previous chapter, it has been mentioned that the purpose of analysis of the upper fan unit is to obtain the necessary chimney output data of the oven cavity. To validate the results of this study, an experimental study has been carried out on the upper fan unit of the oven.

Since the steady state analysis of the upper fan unit has been carried out as isothermal, only the air flow inlets and outlet of the unit's front side is needed for validation process. A total number of ten thermocouples have been placed periodically at the selected points of the unit to obtain the necessary air flow data.

Six out of ten of the thermocouples have been placed on the air flow inlet of the unit. The rest of the thermocouples have been placed on the air flow outlet of the unit. After closing the oven door, experiments have been started. Air flow data have been recorded every 0.3 second over the duration of approximately five minutes. After completing the experiments, average flow data of the entire inlet and outlet of the unit have been obtained to validate the numerical study.

3.1.1 Validation of the Steady State Analysis of the Upper Fan Unit

The results of the numerical study, experimental study and their mean difference have been shown in Table 3.1.

Table 3.1 Comparison of the numerical and the experimental studies for the upper fan unit.

Data	Numerical Study	Experimental Study	Mean Difference (%)
Average Velocity Inlet (m/s)	2.143	2.183	1.832
Average Velocity Outlet (m/s)	5.906	6.611	10.664

A maximum of 10.664 % mean difference has been occurred between the numerical study and experimental study. In the study of Mistry, Ganapathisubbu, Dey & Castillo (2006), it is mentioned that these differences are within acceptable limits, so that the numerical results of the fan unit have been concluded to be reliable.

3.2 Experimental Study of the Oven Cavity

The experimental study of the oven cavity has been carried out in a two-step process. These steps are as follows:

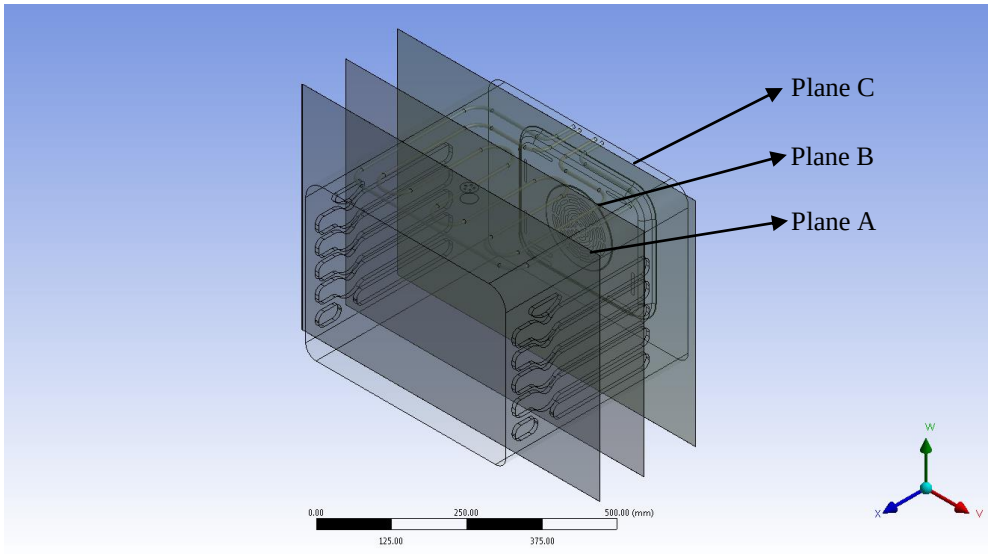
- Obtaining the air flow data around the case of the turbo fan of the oven cavity.
- Obtaining the transient temperature distribution inside the oven cavity.

3.2.1 Obtaining the Air Flow Data Around the Case of the Turbo Fan of the Oven Cavity

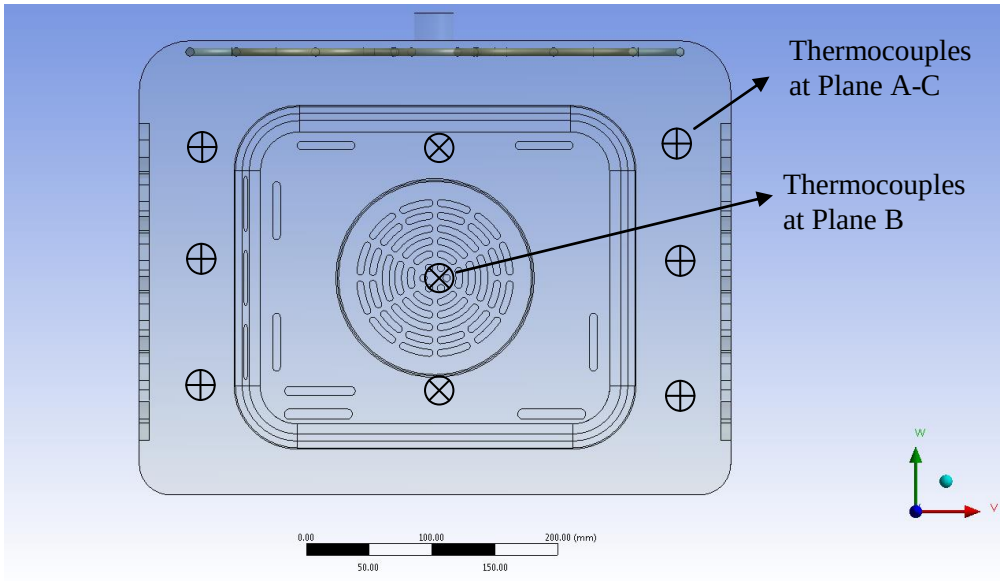
To obtain the air flow data around the case of the turbo fan of the oven cavity fourteen thermocouples have been placed around the case. The thermocouples have been placed according to the faces which were shown in Figure 2.15.

3.2.2 Obtaining the Transient Temperature Distribution Inside the Oven Cavity

Location of the thermocouples in the experiment setup for obtaining the transient temperature distribution inside the oven cavity has been shown in Figure 3.1.



a.



b.

Figure 3.1 Arrangement of thermocouples: (a) Arrangement planes, (b) Locations

As shown in Figure 3.1 a total number of fifteen thermocouples have been placed inside the oven cavity for this experiment. Figure 3.1.a shows the arrangement planes of the thermocouples. While three of the thermocouples have been placed at the center of the oven (Plane B), rest of the thermocouples have been placed so that both Plane A and C have six thermocouples. The Plane A and C have been placed between the center of the oven and front and back sides of the oven. The difference of these thermocouples has been shown in Figure 3.1.b with different images.After placing the thermocouples, the oven has been operated at the pyrolytic function. The

temperature distribution data of the oven has been obtained every 5 seconds over the duration of approximately 5430 seconds.

3.3 Validation of the Steady State Analysis of the Oven Cavity

In the previous chapter, it has been mentioned that the operation of the oven should be considered as transient. The steady state approach has been used as a comparison tool for the transient analysis of the oven. To validate the steady state analysis of the oven cavity, average temperature of one cycle of the pyrolytic function has been calculated from the obtained experimental data of the transient temperature distribution of the oven cavity and the comparison is shown in Table 3.2.

Table 3.2 Comparison of the numerical and the experimental studies for the steady state analysis of the oven.

Location of the Thermocouple	Experimental Study Temperature (K)	Numerical Study Temperature (K)	Mean Difference (%)
Center Top	766	757.67	1.03
Center	729	751.71	3.11
Center Bottom	710.49	751.30	5.74
Front Left Top	737.86	750.11	1.66
Front Left	719.56	750.43	4.29
Front Left Bottom	708.78	749.95	5.81
Front Right Top	760.73	755.44	0.70
Front Right	729.12	753.08	3.29
Front Right Bottom	707.36	748.38	5.80
Back Left Top	707.92	754.96	6.64
Back Left	719.56	751.60	4.45
Back Left Bottom	708.78	749.78	5.78
Back Right Top	707.92	755.48	6.72
Back Right	735.30	744.23	1.21
Back Right Bottom	722.57	749.46	3.72

As seen from Table 3.2, a maximum of 6.72 % mean temperature difference has been occurred between the numerical study and experimental study. This difference is within acceptable limits, so that the numerical results for the steady state analysis of the oven cavity have been concluded to be reliable.

3.4 Validation of the Transient Analysis of the Oven Cavity

Validation for the transient analysis of the oven cavity has been completed by comparing the cycle times of the pyrolytic function of the oven and transient temperature changes during these cycles between the numerical and experimental studies. The comparison of the transient temperature changes during the cycles of the oven is shown in Figure 3.2.

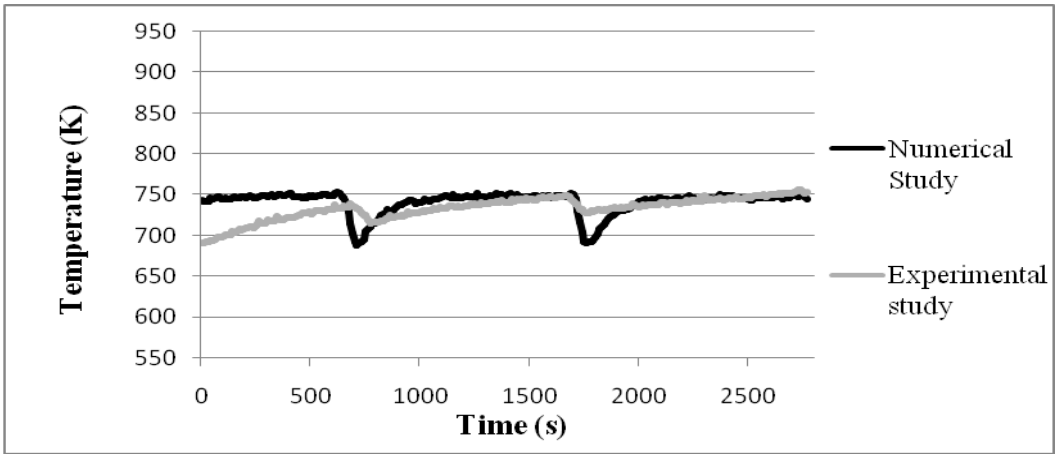


Figure 3.2 The comparison of transient temperature changes during the cycles.

As seen from Figure 3.2, numerical study and experimental study shows a similar method of working during cycles of the pyrolytic function of the oven. The comparison of the cycle times between numerical study and experimental study also shown in Table 3.3.

Table 3.3 Comparison of the cycle times for the numerical and experimental studies of the transient analysis of the oven cavity.

Cycle Number	Numerical Study (s)	Experimental Study (s)	Mean Difference (%)
1	630	694	9.221902017
2	1070	982	8.961303462
3	1070	1094	2.193784278

A maximum of 9.22 % mean difference has been occurred between the numerical study and experimental study. This difference is within acceptable limits, so that the numerical results for the transient analysis of the oven cavity have been concluded to be reliable.

In all of these analyses, mean differences were calculated dividing the difference of the results of the experimental and numerical studies by the results of the experimental studies.

CHAPTER FOUR
RESULTS AND DISCUSSIONS

4.1 Results of the Steady State Analysis of the Upper Fan Unit of the Oven

As mentioned before, the purpose of the steady state analysis of the upper fan unit of oven was to obtain the chimney output data required for the remaining analyses of the oven cavity. After validating the analysis using the results of the experimental study, the completed analysis of the unit has been transferred to the program's post-process utility.

The chimney output data has been obtained from the post-processor module's function calculator which was calculated as 4.021 m/s. This data has been used in the remaining analyses as a boundary condition.

4.2 Results of the Steady State Analysis of the Oven Cavity

To investigate the heat transfer and air flow characteristics of the steady state analysis of the oven cavity, velocity and temperature contours of the cavity have been created, using the Planes A, B and C which was shown in Figure 3.1.a. These contours were shown in Figures 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6.

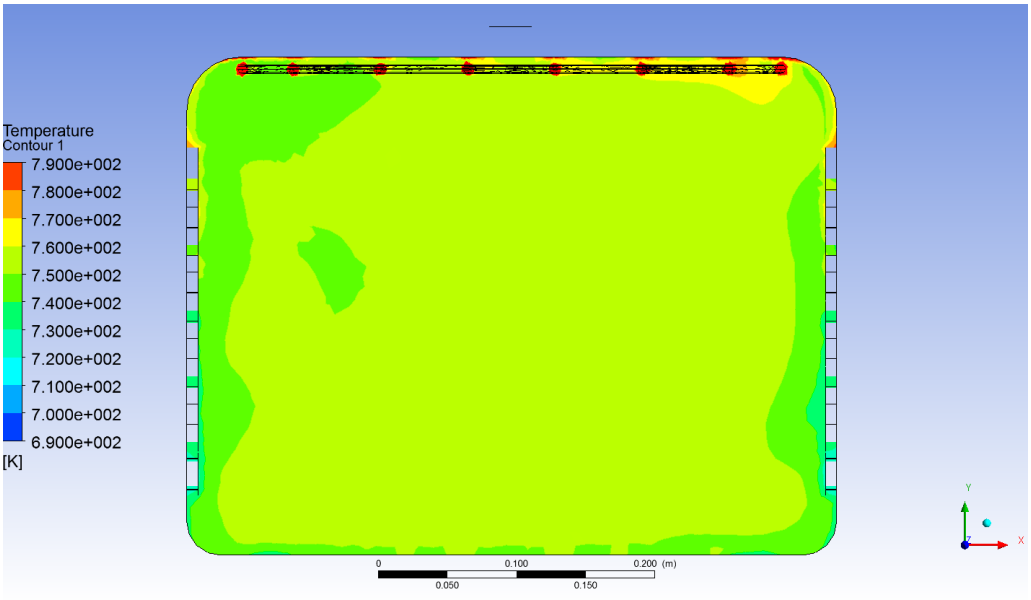


Figure 4.1 The temperature contour of the Plane A.

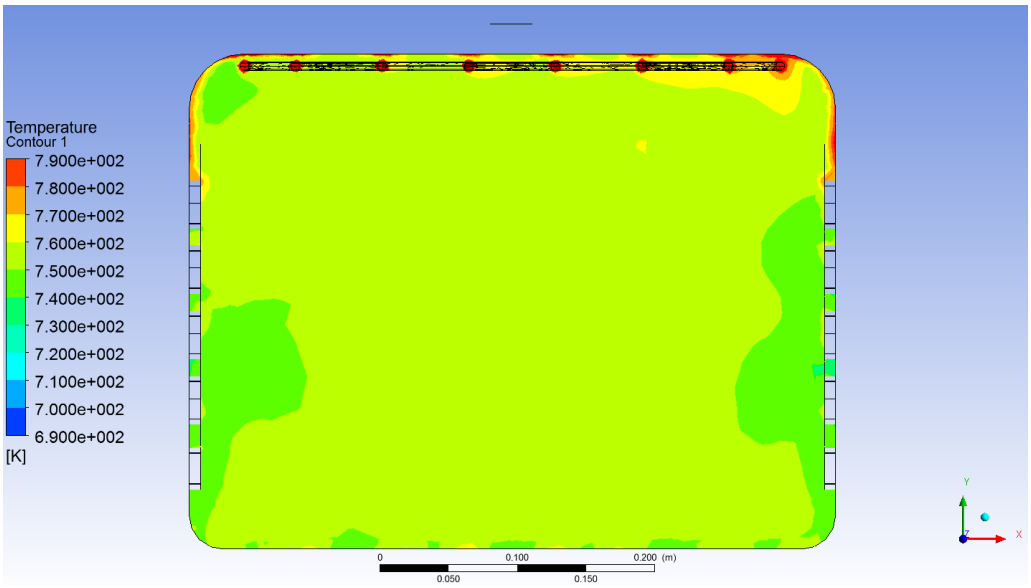


Figure 4.2 The temperature contour of the Plane B.

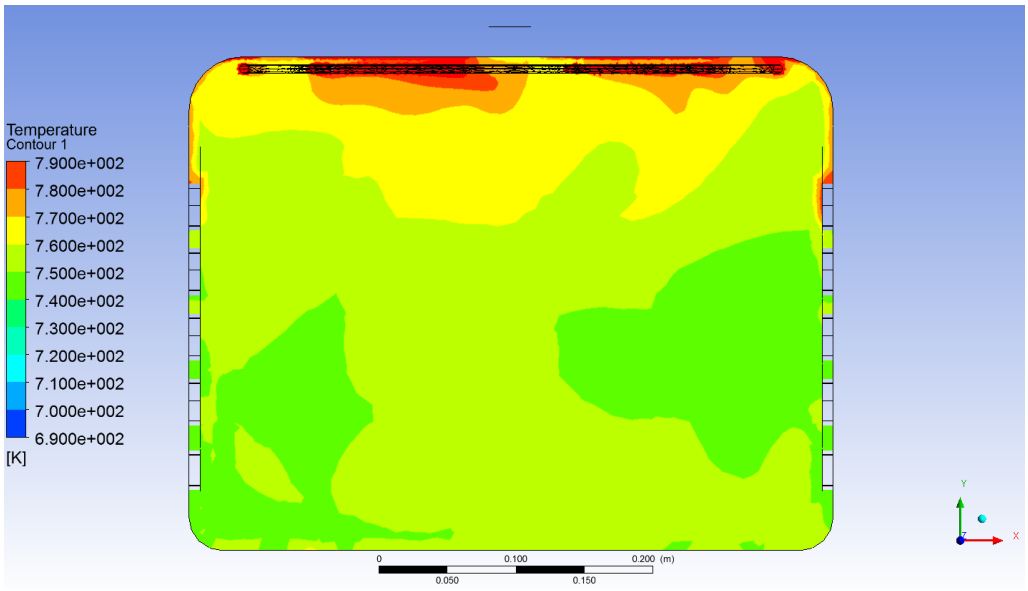


Figure 4.3 The temperature contour of Plane C.

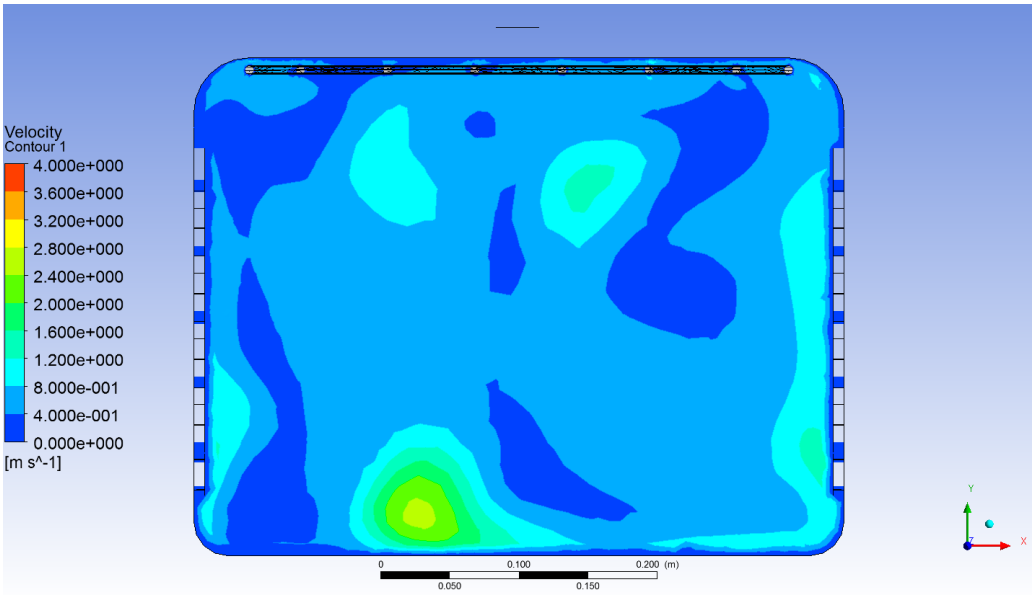


Figure 4.4 The velocity contour of Plane A.

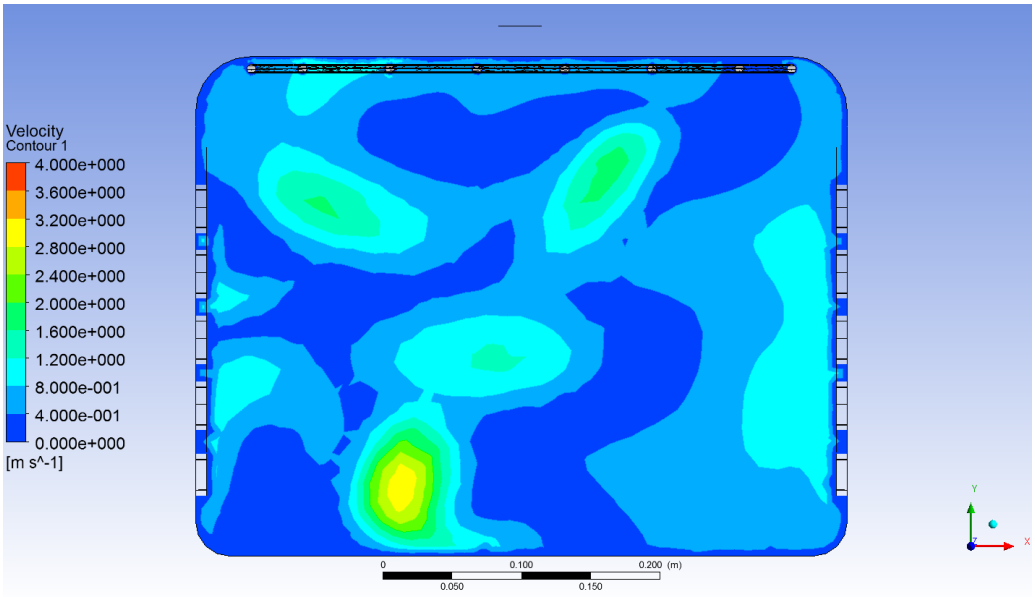


Figure 4.5 The velocity contour of Plane B.

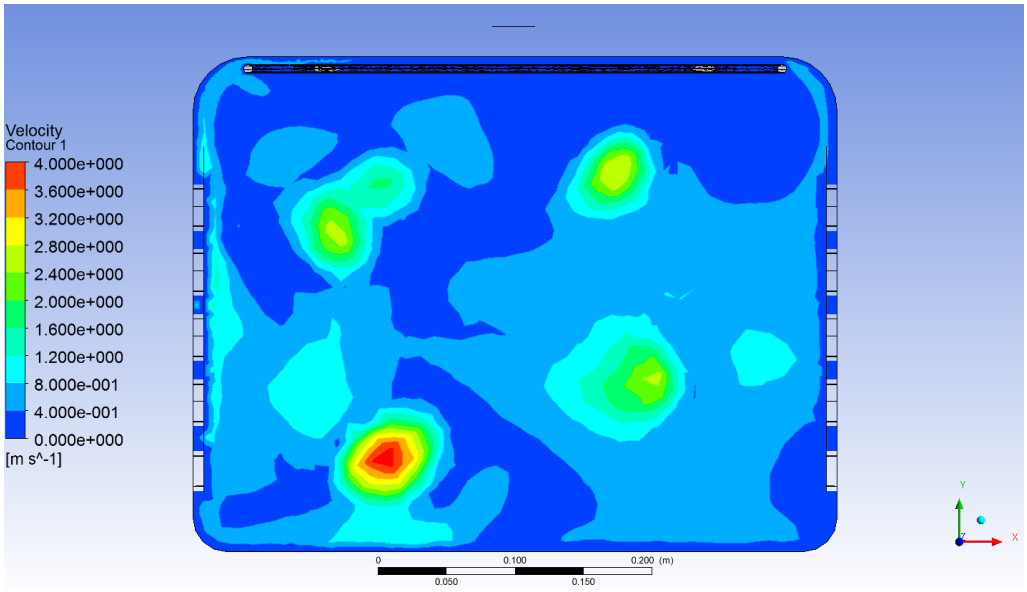


Figure 4.6 The velocity contour of Plane C.

In Figures 4.1, 4.2 and 4.3 the temperature contours show that the temperature of the oven is the lowest at the Plane A which is closest to the oven door. This result is consistent, since the most important heat loss in the oven occurs from the oven door. The forced convection caused by the turbo fan of the oven also strengthens this effect. The heat loss caused by the forced convection also can be seen at the walls of the oven. The case around the turbo fan designed to have more holes at the left side of the case, and the result of this can also be seen in the temperature contours. Left

side of the wall has a higher heat loss because of these holes, and has a lower surface temperature than the other side of the wall.

The velocity contours of the oven also show consistent results. Maximum velocity values of the oven are at the Plane C which is the closest to the turbo fan. The effects of the turbo fan case can also be seen in the velocity contours. The left side of the oven has higher air flow velocity because; this side of the case has more velocity inlets than the other side of the case.

4.3 Results of the Transient Analysis of the Oven Cavity

To show the results of the temperature distribution in the oven cavity for the transient analysis, temperature contours have been created for selected time steps at the Plane B of the oven. The second cycle of the function which was shown in Figure 3.6 has been selected for obtaining the results. This cycle has been investigated from the start of the cycle to the end of the cycle. By doing this, the heating process of the oven throughout the cycle has been analyzed.

The second cycle of the function completed in 1070 seconds as seen from Table 3.2. An interval of 1200 seconds which contains the whole of the second cycle has been used for investigation. The temperature contour results for every 100 seconds of the total of 1200 seconds have been shown in Figures 4.7 to 4.19.

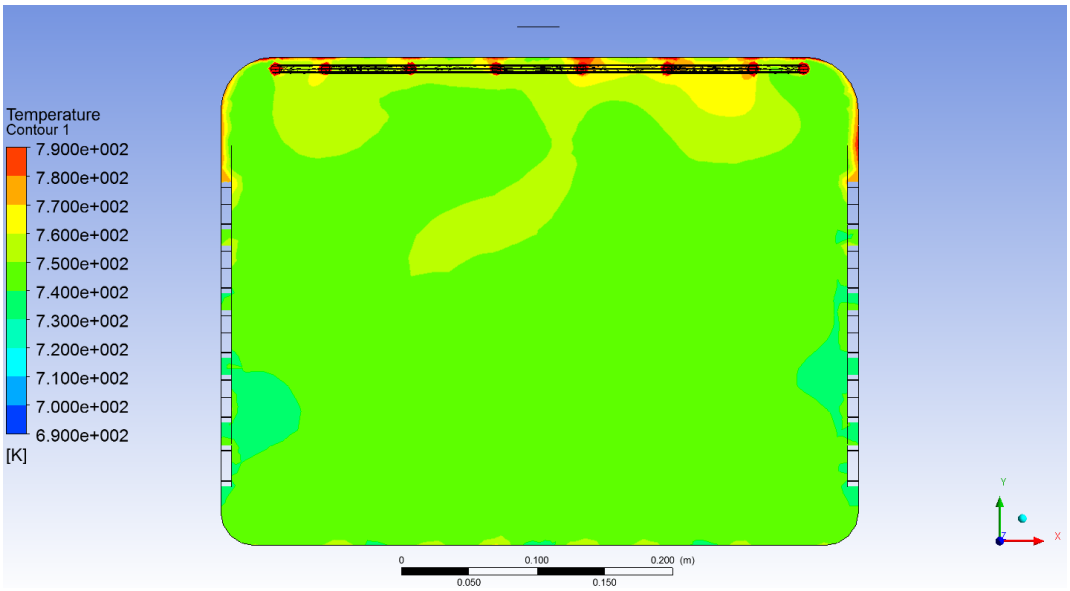


Figure 4.7 The temperature contour at t = 0 s.

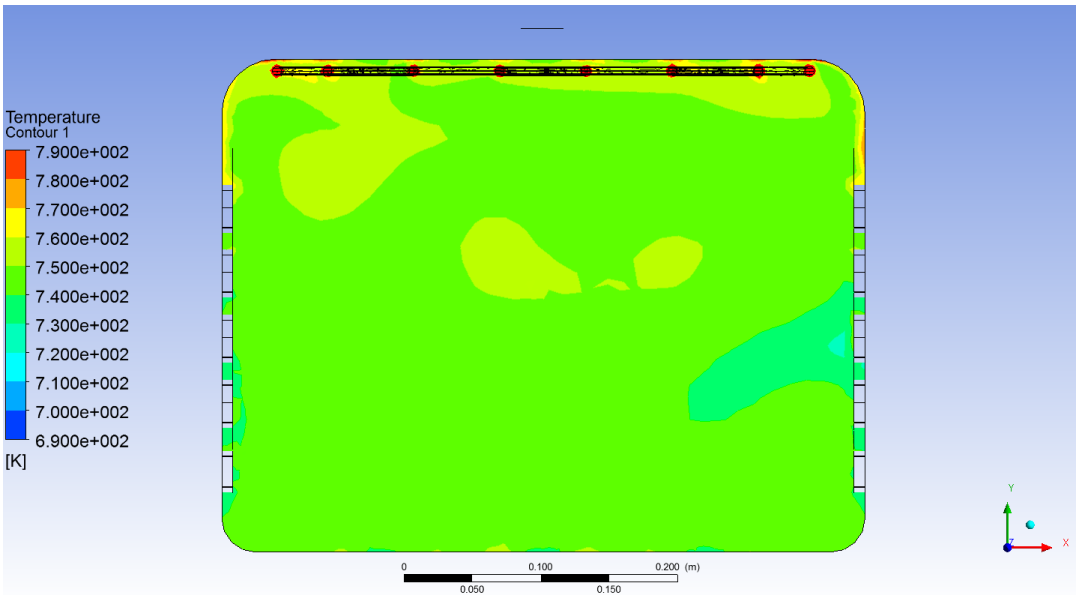


Figure 4.8 The temperature contour at t = 100 s.

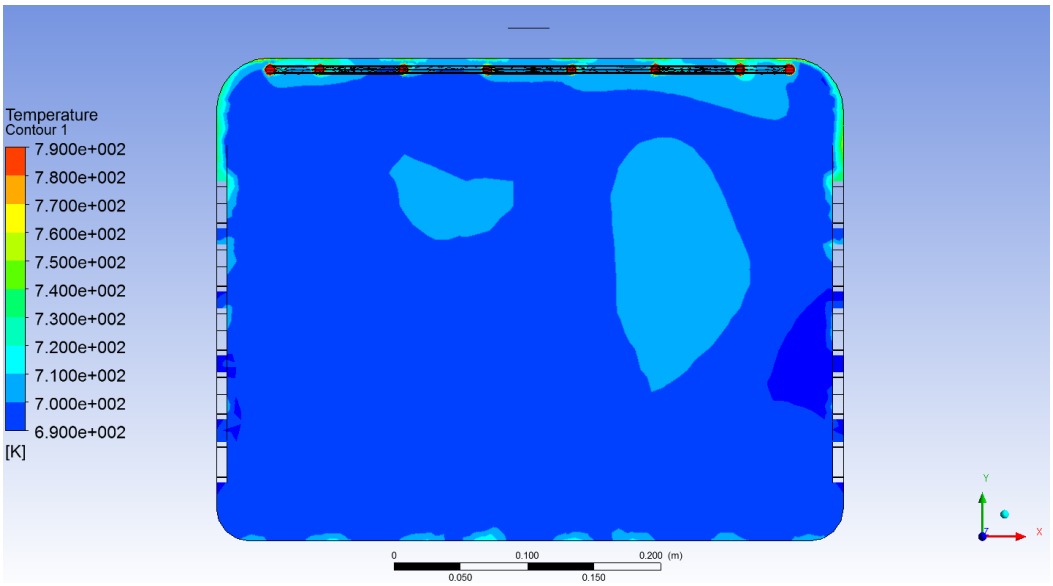


Figure 4.9 The temperature contour at t = 200 s.

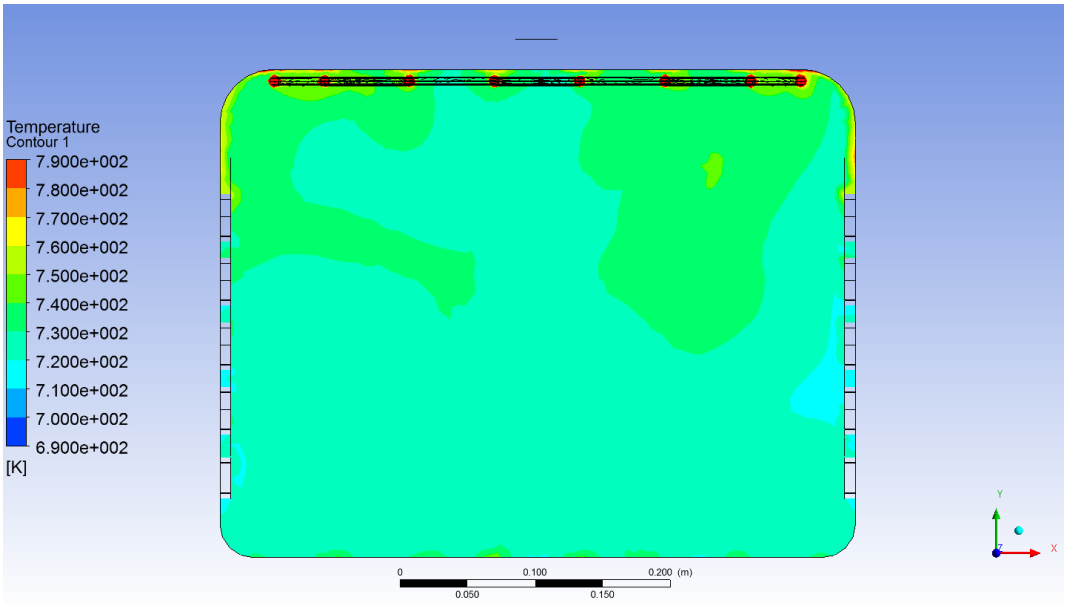


Figure 4.10 The temperature contour at t = 300 s.

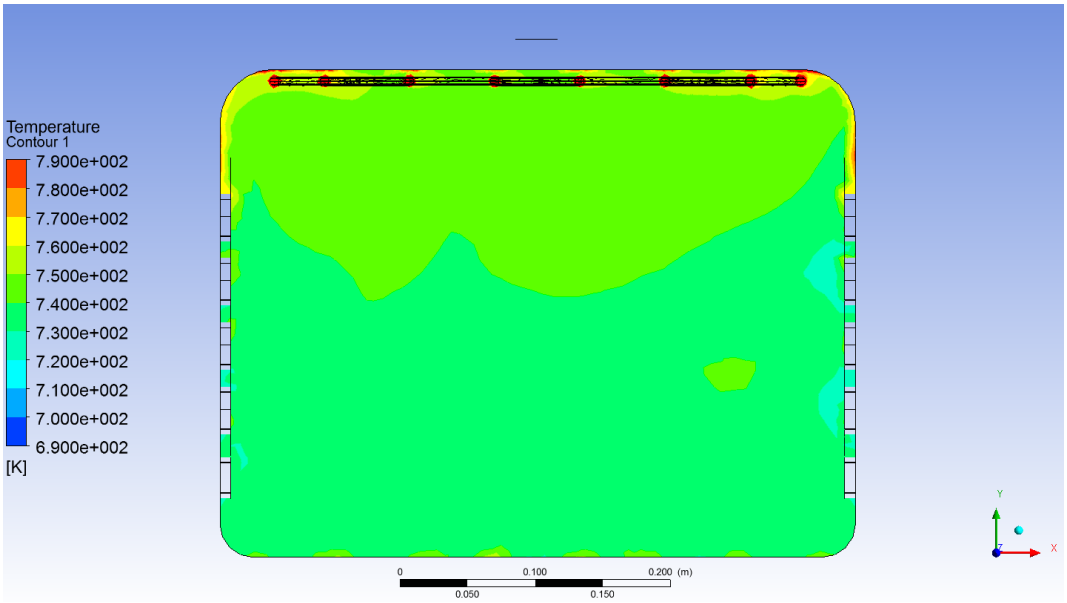


Figure 4.11 The temperature contour at t = 400 s.

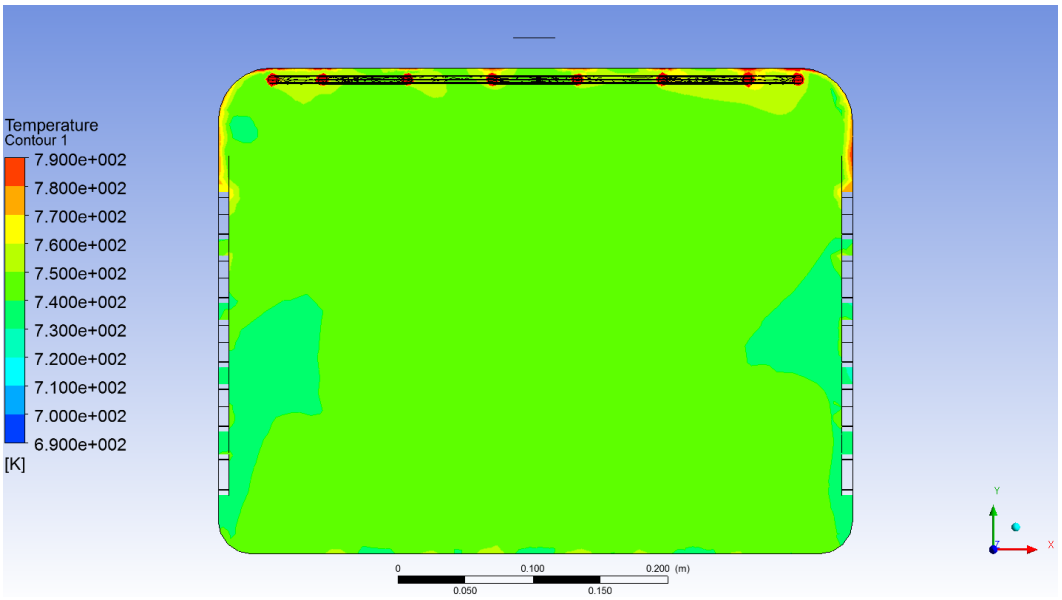


Figure 4.12 The temperature contour at t = 500 s.

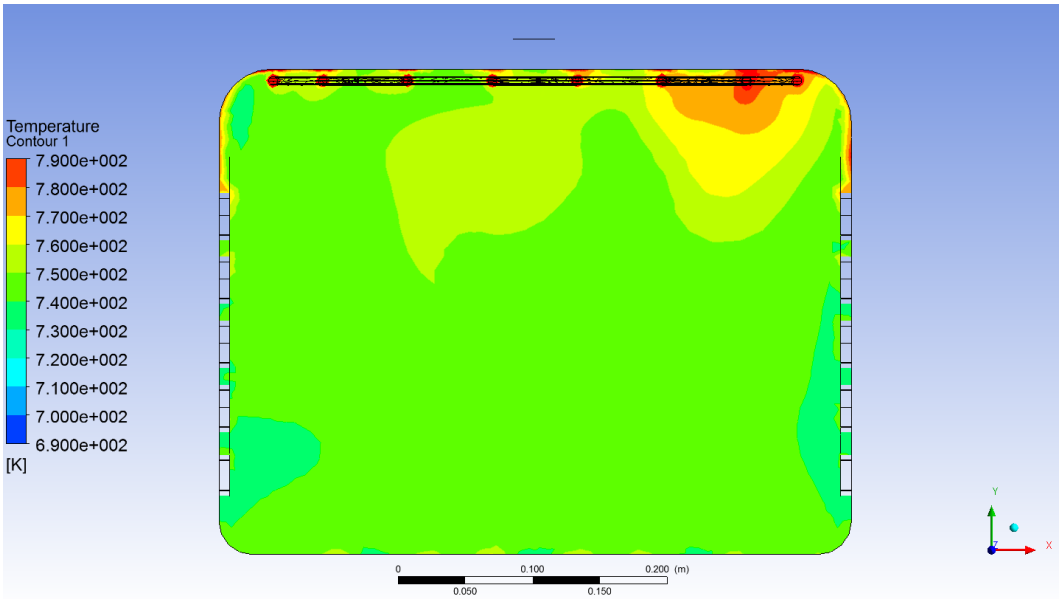


Figure 4.13 The temperature contour at t = 600 s.

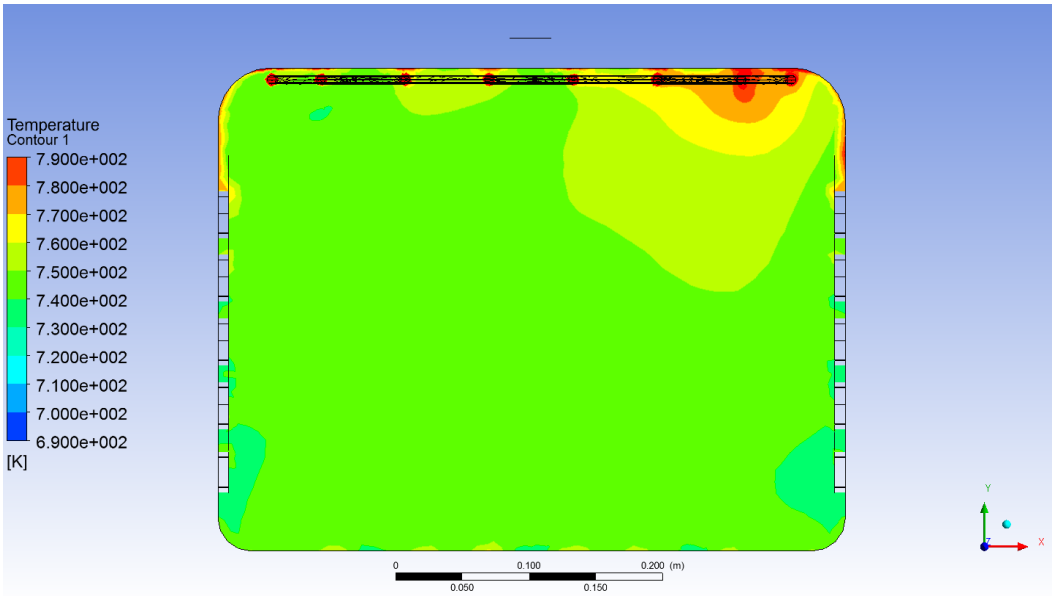


Figure 4.14 The temperature contour at = 700 s.

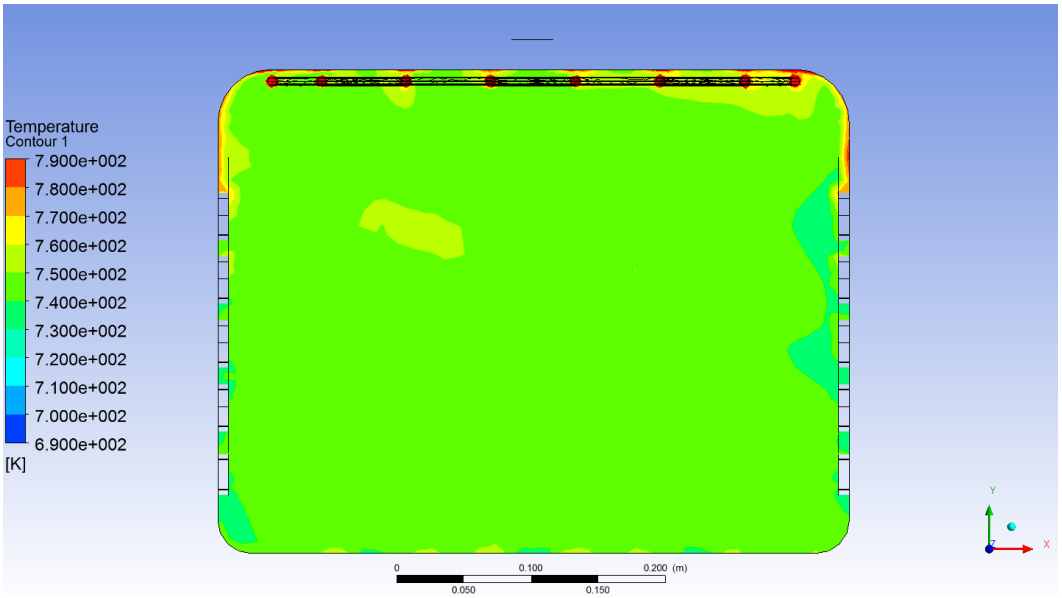


Figure 4.15 The temperature contour at t = 800 s.

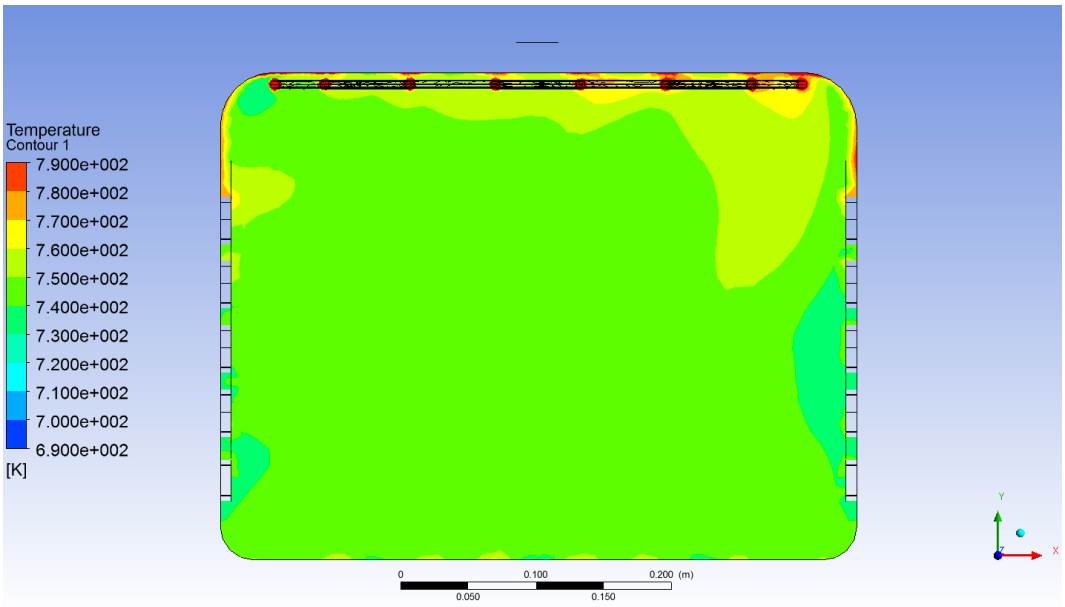


Figure 4.16 The temperature contour at t = 900 s.

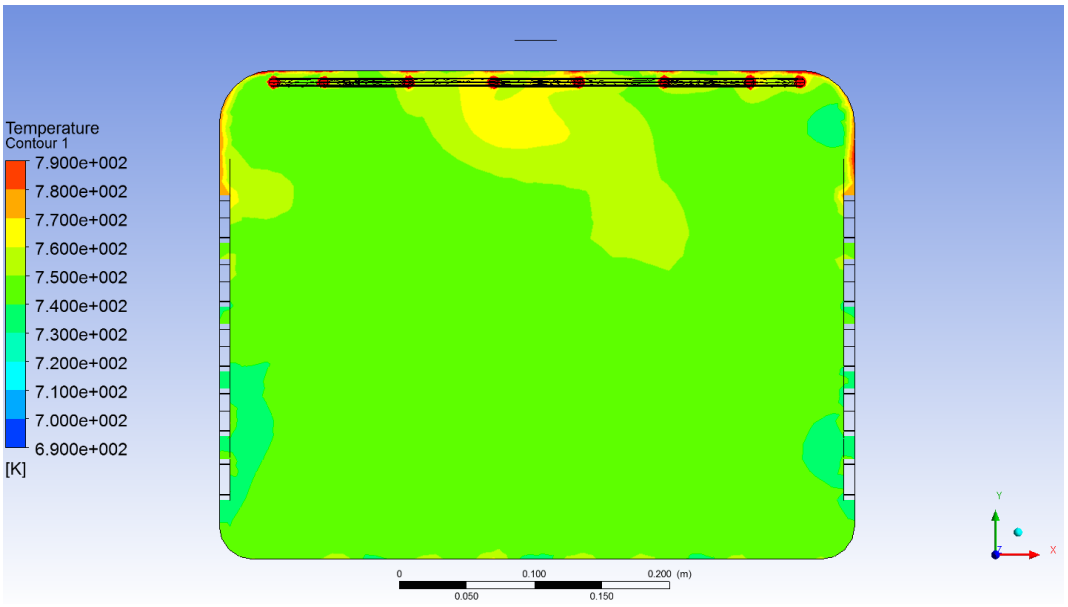


Figure 4.17 The temperature contour at t = 1000 s.

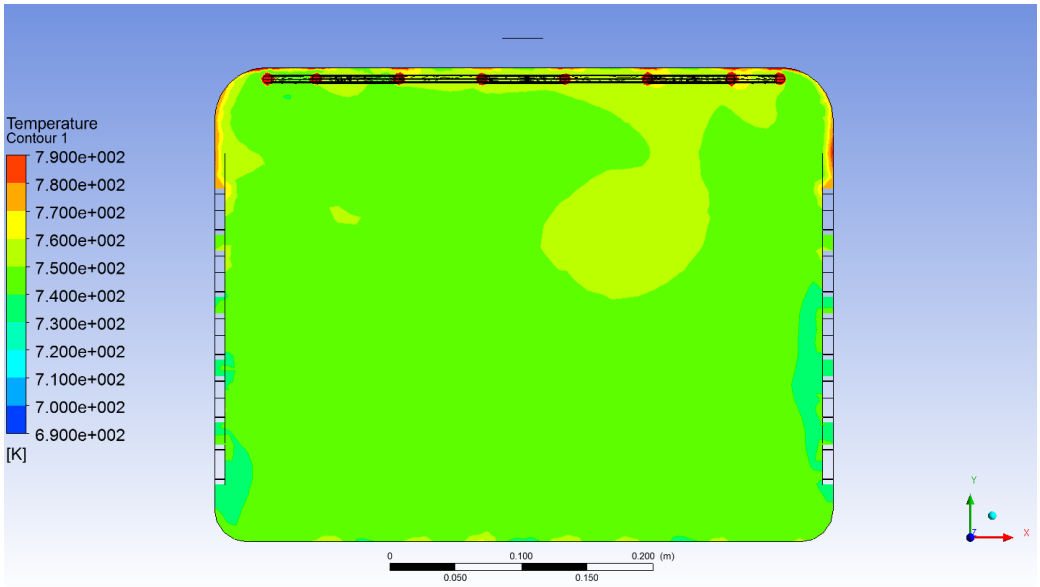


Figure 4.18 The temperature contour at t = 1100 s.

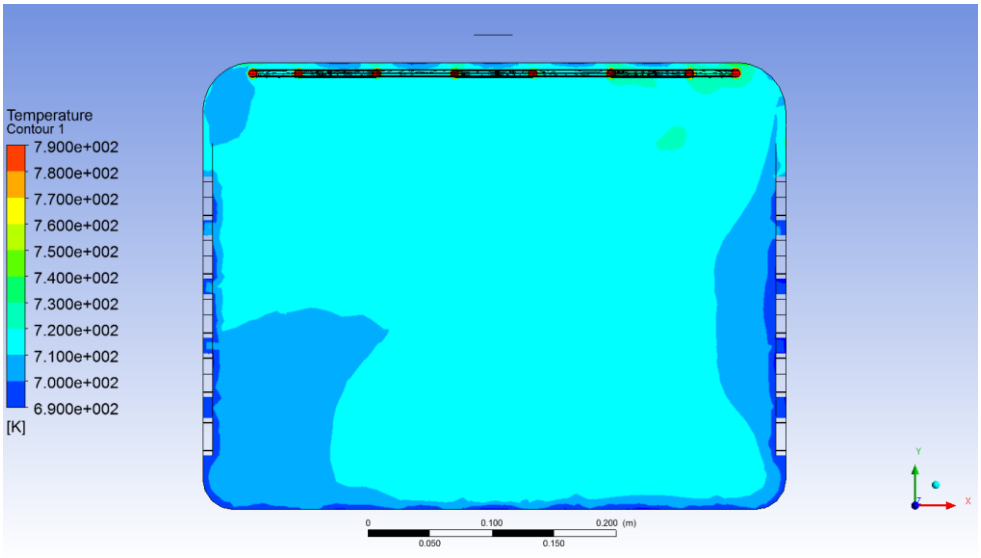


Figure 4.19 The temperature contour at t = 1200 s.

The velocity contours of the analysis also have been created at the same locations and for the same cycle to investigate the air flow characteristics inside the oven cavity. These contours have been shown in Figures 4.20 to 4.32.

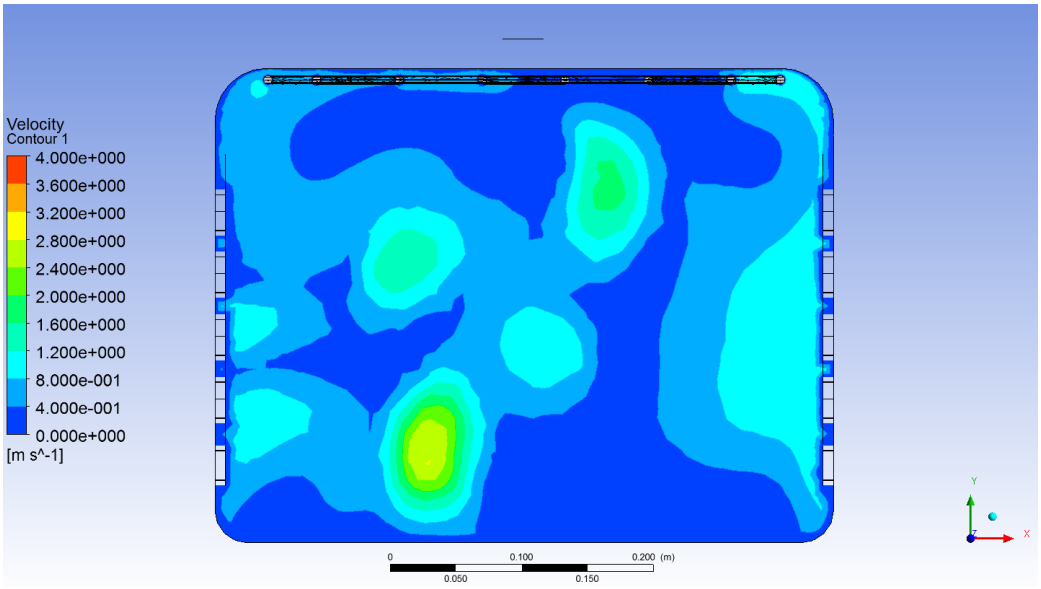


Figure 4.20 The velocity contour at t = 0 s.

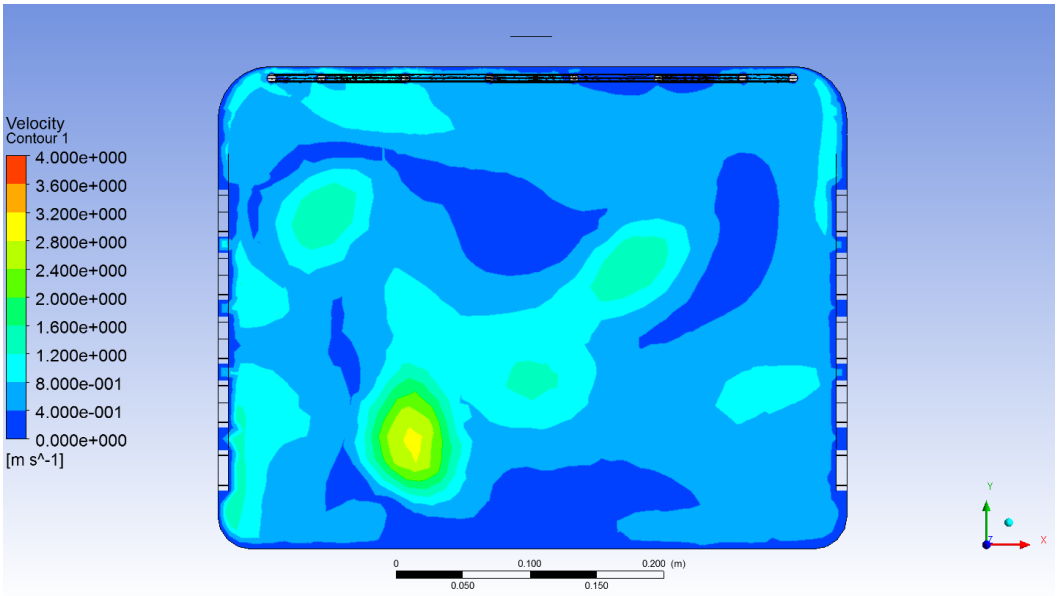


Figure 4.21 The velocity contour at t = 100 s.

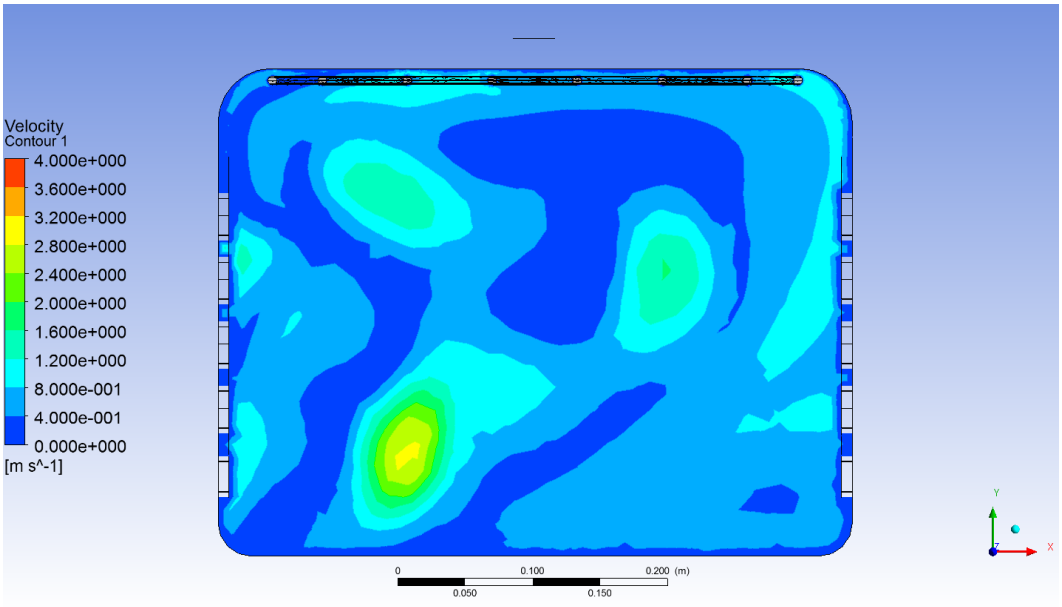


Figure 4.22 The velocity contour at t = 200 s.

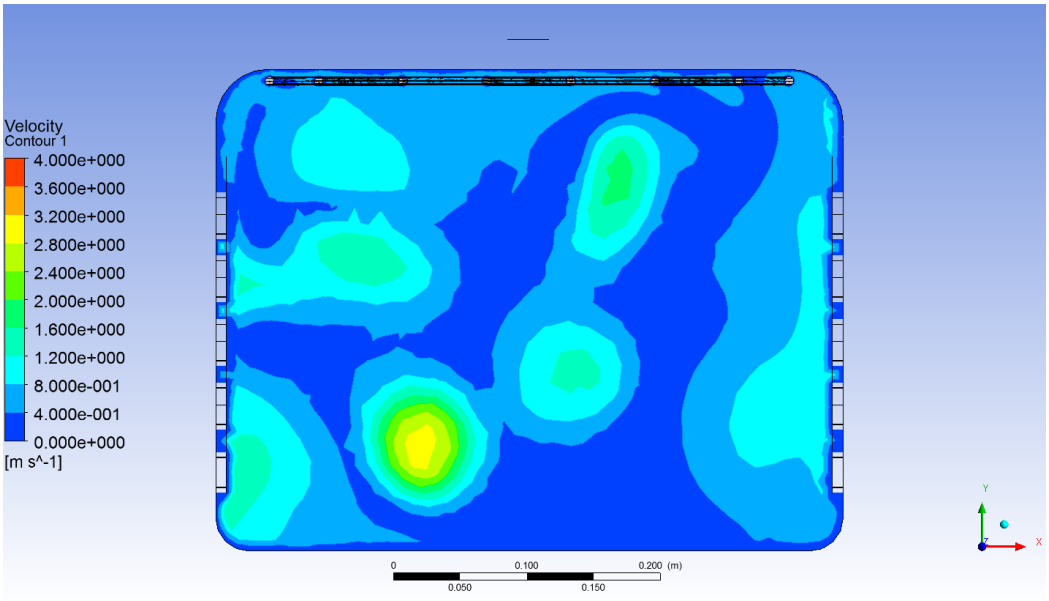


Figure 4.23 The velocity contour at t = 300 s.

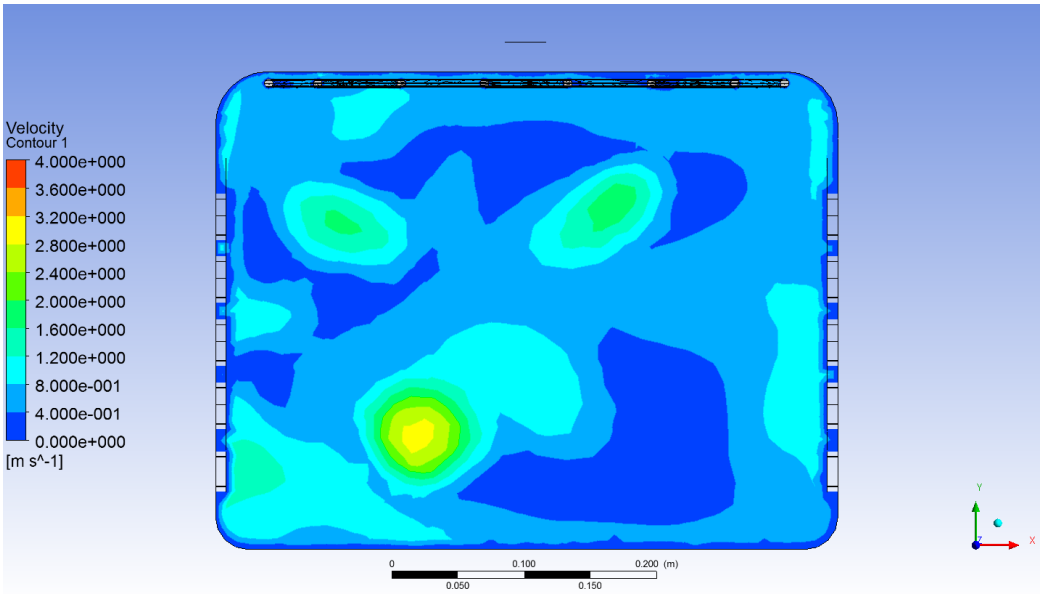


Figure 4.24 The velocity contour at t = 400 s.

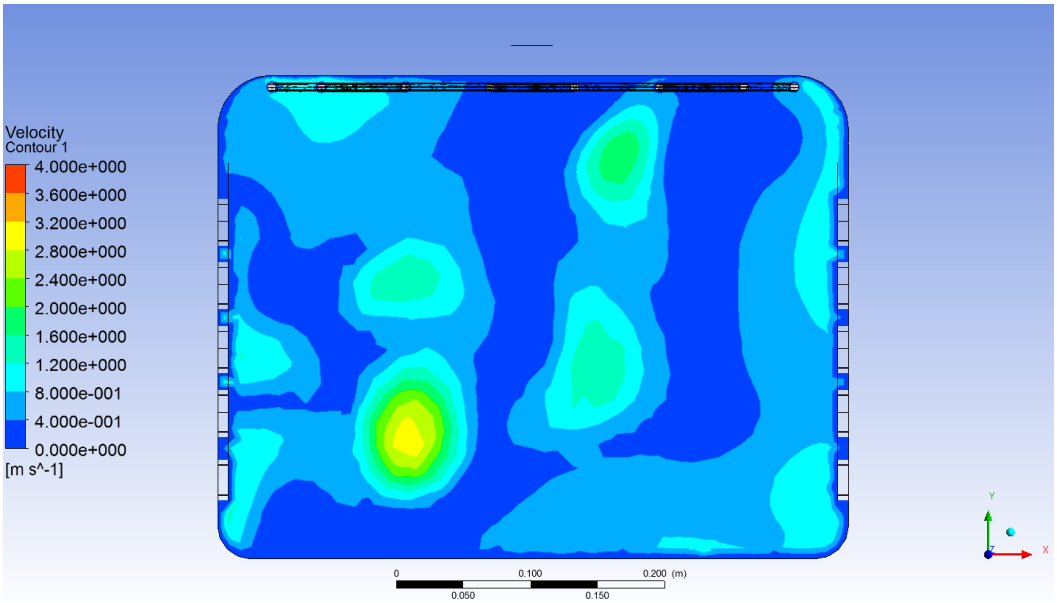


Figure 4.25 The velocity contour at t = 500 s.

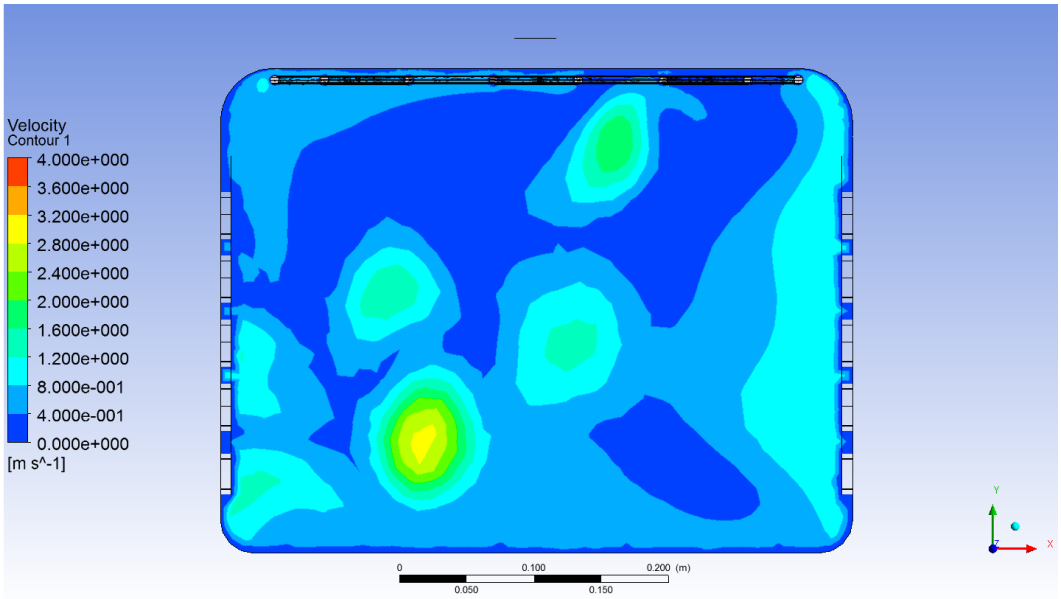


Figure 4.26 The velocity contour at t = 600 s.

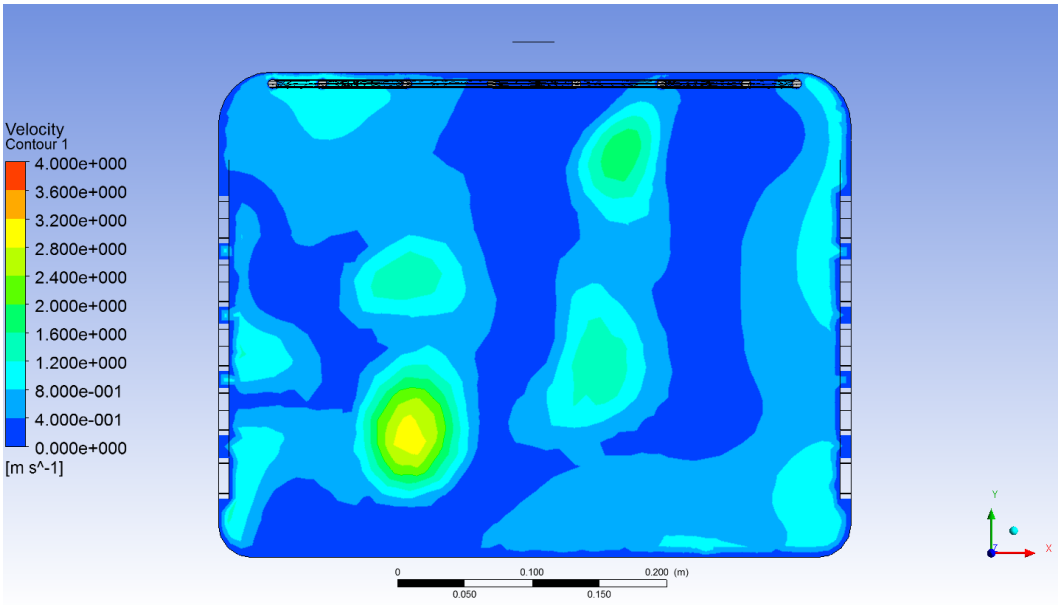


Figure 4.27 The velocity contour at t = 700 s.

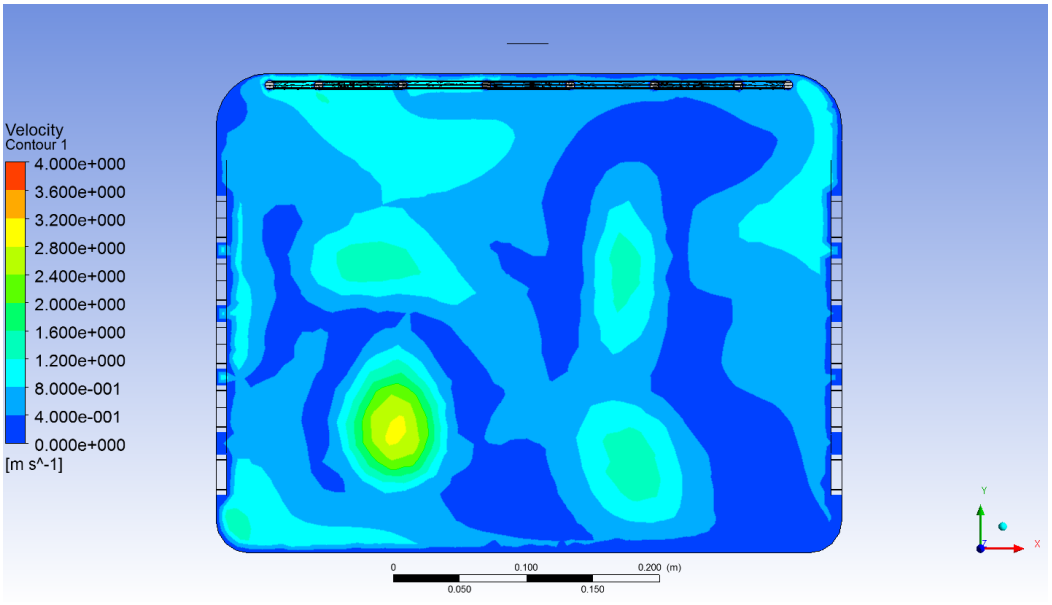


Figure 4.28 The velocity contour at t = 800 s.

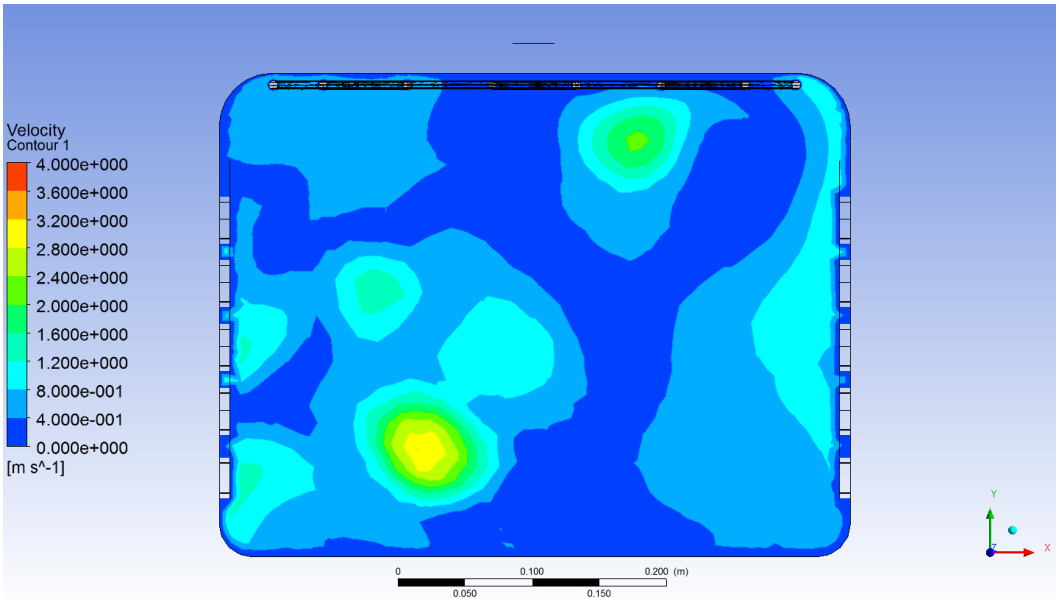


Figure 4.29 The velocity contour at t = 900 s.

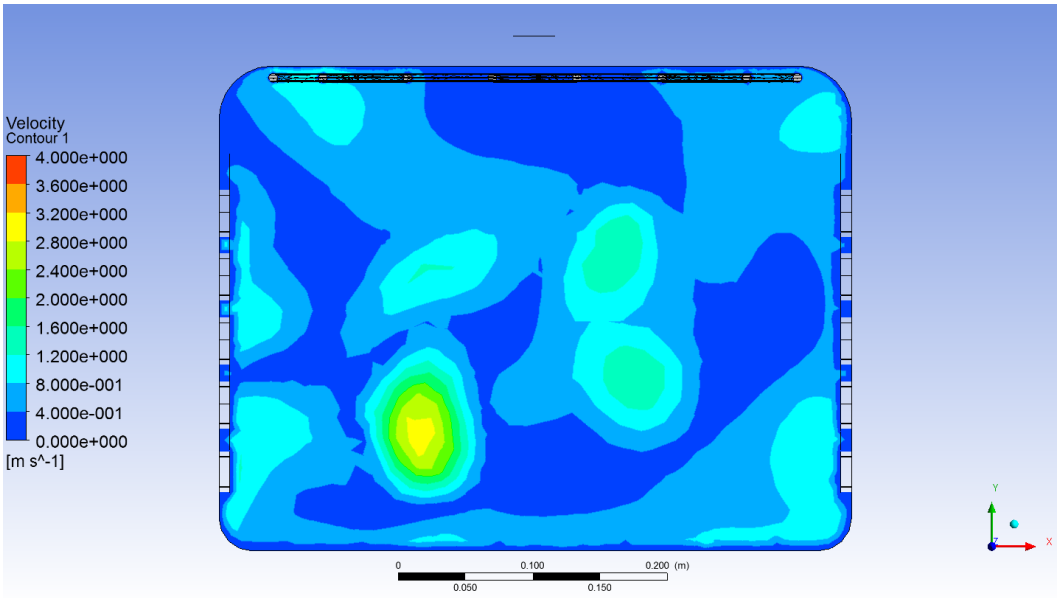


Figure 4.30 The velocity contour at t = 1000 s.

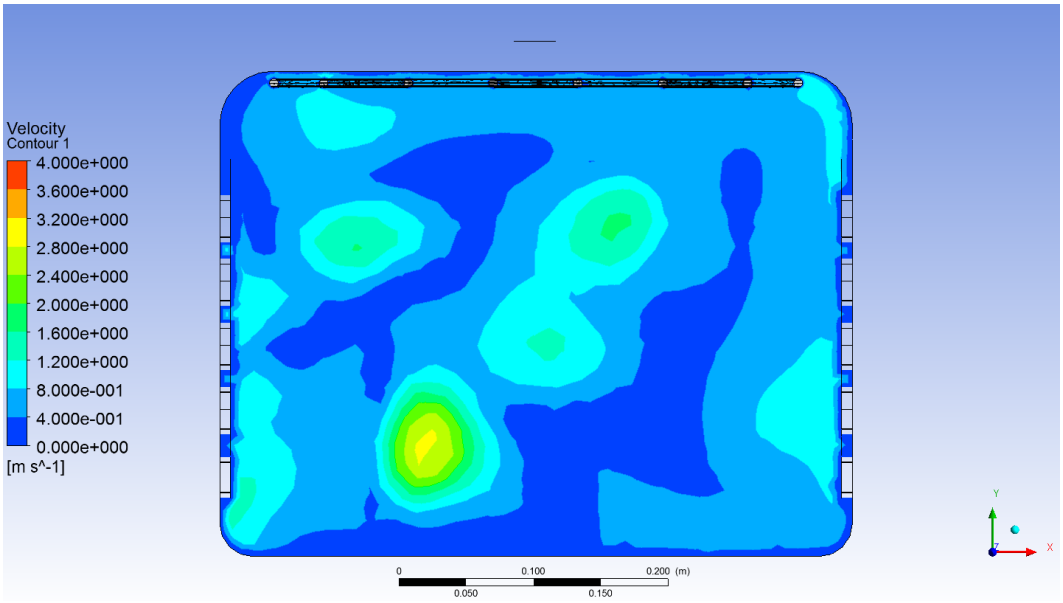


Figure 4.31 The velocity contour at t = 1100 s.

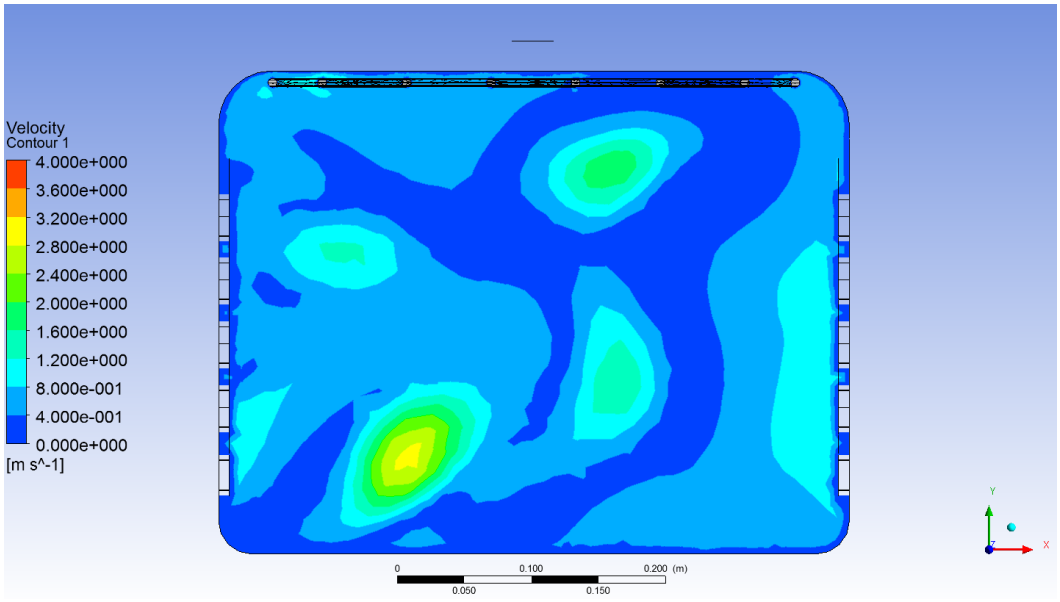


Figure 4.32 The velocity contour at t = 1200 s.

The temperature contours of the selected cycle shows that, when the oven reaches the preset maximum temperature value between t = 100 s and t = 200 s (Figures 4.9 and 4.10), the oven cavity starts to cool down because of the thermostat control until the heaters start up again after reaching the tolerated temperature value. The

remaining contours show the heating process of the rest of the cycle (Figures 4.11 to 4.19).

Since the purpose of the pyrolytic function of the oven is to self-clean the walls of the oven, the temperature distribution around the walls throughout the cycle is important. The upper wall of the oven has the highest temperature is the oven because of its proximity to the heaters of the oven. As seen from the temperature contours, the left side of the oven heats faster than the right side of the oven. The reason behind is the velocity inlets of the turbo fan unit which were shown in Figure 2.15.

The effects of these inlets also can be seen from the velocity contours of the oven. The left side of the oven has higher velocity values because of the inlets. The effects of the design of the turbo fan case can be easily detected using the transient results.

When the steady state results and the transient results compared, it is found that even though the steady state analysis can be used as a prediction tool for the oven, it cannot be used for analyzing the whole process cycles while the transient approach presents a better understanding for analyzing the cycles of the oven.

CHAPTER FIVE
CONCLUSIONS

The aim of this thesis is to investigate the heat transfer and fluid (air) flow characteristics of domestic ovens by implementing numerical and experimental methods. A prototype pyrolytic domestic oven has been used in these studies. In literature researches, both transient and steady state analyses for investigating the heat transfer and air flow inside oven cavities for different studies were examined. By developing a combined examination method of steady state analysis and transient analysis, heat transfer and fluid flow characteristics have been investigated.

For numerical study, three different 3-D models of interior air volumes of both the oven cavity and the upper fan unit of the oven were prepared and Computational Fluid Dynamics and Heat Transfer (CFDHT) analyses were made. The prepared models of these analyses have been validated with the experimental data which were obtained from the experimental studies.

The upper fan unit of the oven has been analyzed for the chimney output of the oven cavity. The results of this analysis showed a maximum of 10.664 % mean difference between the experimental results.

The steady state thermal analysis of the oven cavity has been completed for the purpose of comparison with the transient analysis of the oven cavity. Thermal equilibrium has been obtained as a result of the steady state approach of this analysis. The reason behind this is that the thermostat control was not operational for this approach. The results of this analysis showed a maximum of 6.72 % mean difference between experimental results.

To implement the thermostat control of the oven effectively, a FORTRAN code has been used in transient analysis of the oven cavity. This code worked cooperatively with the solver as an external source which gained its necessary data

from the solver after every time step of the analysis. By using the FORTRAN code, transient analysis of the oven has been able to simulate the thermostat control of the prototype oven. The results of the transient analysis of the oven showed a maximum of 9.22 % mean difference between experimental results.

By using this method, the temperature and air velocity distributions have been investigated inside the oven cavity. At key locations such as near the walls of the oven, the temperature changes during a full cycle of the pyrolytic function of the oven have been investigated. The investigation showed that the temperatures of the walls change over time with various reasons such as the changing of velocity distribution inside the cavity.

It is possible to reduce prototype costs and times by implementing this method. The effects such as changing the model fan case or selecting a different insulation type can be done numerically to examine the possible results by implementing similar analyses.

This thesis is taking placement under 3130615 numbered TÜBİTAK – TEYDEB project and scope of this thesis is to provide and develop an investigation method for heat transfer and fluid flow characteristics for domestic ovens.

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