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Cooking Performance Optimization with New Types of Fan Baffles in Domestic Built-in Ovens

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Abstract – With the new technologies and harder global regulations, improvement of household appliances increases gradually. By the same reason, electrical built-in ovens need to have better cooking performance for the user satisfaction to be able to eat qualified cooked foods. This paper investigates better cooking performance in forced ventilated domestic electrical built-in oven by improving the uniformity of heat distribution in the cavity by retrofitting current fan cover. For this study, both experimental and numerical methods are used. Numerical method is applied by using Computational Fluid Dynamics (CFD) program which is FloEFD. As a first attempt, CFD results are evaluated for acceptable compatibility with experimental results, then modifications are implemented by using CFD. In this study, Haier Europe commercial oven is used as a reference model of fan cover. 7 different modifications are performed to fan cover. First modification is related to intake design of fan cover, other modifications included U-shaped fan cover with the different blowing holes options. Results showed that, with the new design U-shaped fan cover has better internal heat distribution inside cavity than current design. Best configuration is tried out in Haier Europe laboratory and CFD results are confirmed.

***Keywords*:** Domestic oven, CFD, FloEFD, Cooking Performance, Fan Cover

1. Introduction

The development of the household appliances and their technologies is one of the key targets of producers to improve their R&D improvements. In the area of domestic ovens, cooking performance is one the main design points. New designs to improve cooking performance is needed large quantity of experimental tests with the new modifications. Making lots of experimental test is disadvantage from the effort, time, and resources view. To decrease these advantages, CFD programs can be used. CFD is becoming more popular to decrease time & money for new design in last decades. The use of numerical simulations to heat transfer & air flow studies in domestic ovens has been spread by investigators [1-5]. Uros et al., studied for numerical methodology for the better baking performance of a forced convection oven [6]. They had 6 different fan cover designs and they compared them by using time dependent 3D numerical simulations which radiative and convective heat transfer mechanisms were used. Dong Ho Park et al., studied for electrical heater usage algorithms to improve the cooking process in domestic ovens by using numerical simulations [7]. They achieved better baking process with this study. Mena et al., studied for numerical investigation of thermal conditions provided by electrical oven during Neapolitan pizzas cooking [8]. These all studies show that, numerical simulation is one of the valid methods to improve oven cavity heat distribution.

In this paper, it is researched for the new fan cover design to improve heat distribution inside cavity by using numerical method and experimental method. For the better baking process, numerical model is developed by using FloEFD program, then original design is validated with experimental tests. Then 6 different fan cover modifications are tried by CFD. End of this study, heat distribution is improved inside oven cavity then, best design is confirmed in Haier Europe Laboratory.

2. Methodology

In this study, aim is to create new baffle design for the better cooking performance in the mean of well- distributed temperature along the cakes on trays. As a first step, experimental test is applied with baseline design to understand the current situation. Experimental test is applied in Haier Europe Research and Development Laboratory. Then, CFD study is improved to validate experimental study. CFD model is created using FloEFD package program which has a CAD interface to develop the model. For the governing equations it uses finite volume method. As a turbulence solution, it uses only k-ε model. For the mesh point of view, FloEFD is using cartesian mesh. To obtain space discretization, the axis-oriented rectangular grid is used far from a geometry boundary. Near the geometry boundary Cartesian cut cells approach is used [FloEFD User Guide - 9].

2.1. Oven Description - Modifications

For the experimental tests and CFD analysis, one of the electromechanics built-in ovens in Haier Laboratory is used. The general properties of oven are given below in Table 1.

Table 1 – Oven Properties

Oven Properties	**Values**
Oven Structure	Fan Oven
Upper Resistance	1800W
Turbo Resistance	2200W
Turbo Fan	22W
Total Volume	70L
Control Type	Electromechanics

Haier built-in oven model is shown in Figure 1 below. It is used in experimental study as a base model, and with some simplifications to decrease load of analysis, it is used in CFD analysis.

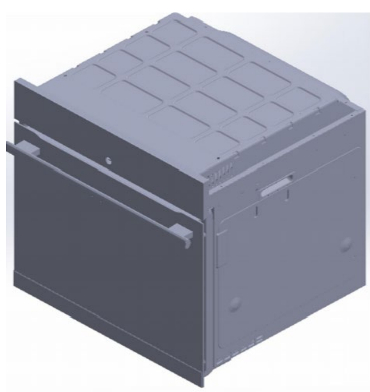

Figure. 1: Haier built-in oven CAD model

The related oven comprises upper heater, turbo heater, turbo fan and turbo fan cover inside of the oven. Base fan cover is shown in Figure 2 below.

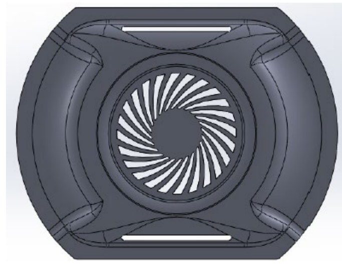

Figure. 2: Base fan cover

After experimental and CFD study are applied to base model, different modifications are tried on CFD analysis. Fan cover design is changed to be able to provide more homogeneous heat distribution inside of the oven during cooking performance tests. Model of new type of fan cover is shown in Figure 3 and modifications are listed in Table 1 below.

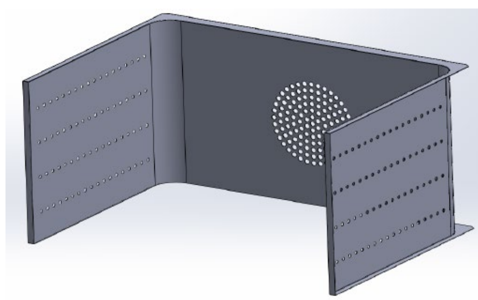

Figure. 3: New type of fan cover

Table 1: Baffle Modifications

Fan Cover Type	Modifications
Type 0	Base Shape – Without U Shape
Type 3	U Profile 4 row – 12 holes of each row – 5mm diameter for each hole
Type 6	U Profile 4 row – 18 holes of each row – 5mm diameter for each hole
Type 13	U Profile 4 row – 18 holes of each row – 10mm diameter for each hole
Type 14	U Profile 4 row – 9 holes of each row – 10mm diameter for each hole

Type 0 which is the original status has both experimental and CFD study. Type 3,6,13 and 14 are applied CFD and Type 6 is tried with experimental test again.

2.2 Experimental Study

In this study, to see the current situation of the oven cooking performance, experimental test is applied in Haier Europe Research and Development Laboratory. During the experimental study, IEC 60350-1 is based for homogenous cooking in domestic ovens. According to this standard, cooking performance is evaluated in two steps. One is homogenous heat distribution, second is enough heat supplement. For the homogenous heat distribution, little cake test is taken as a reference for original baffle study. According to standard, for the forced air function of one tray cooking, oven is set on 160 C, with the pre-heat function, total time should be 40 minutes for little cake cooking.

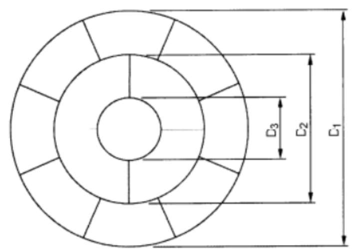

Figure. 4: Evaluating little cake cooking according to IEC 60350-1

As shown in the Figure 4 above, cake is distributed 13 equal regions. D1 is the little cake full dimension, D2 is middle are dimension and D3 is centre are dimension of cake. According to standard, colour scalers are evaluated in the end of the cooking test. In this experimental study, to eliminate the mass transfer in CFD study, test is simplified. In one tray, 16 J type thermocouples are used to measure homogeneity of oven during cooking condition as shown in Figure 5 below.

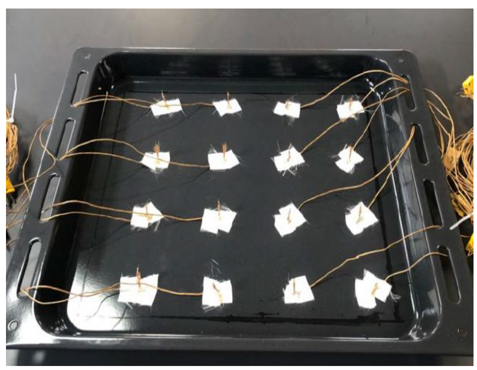

Figure. 5: Cooking tray temperature measurement

Figure. 6: Tray oven position

In the beginning of test, turbo & fan function is activated on 160C set temperature. After pre-heating period, tray is set in middle area of oven as shown in Figure 6 above.

2.3 CFD Study

For decreasing the number of experimental studies, Computational Fluid Dynamics (CFD) method is used in this study. The Reynolds Averaged Navier Stokes equation model is applied instead of Large Eddy Simulation (LES) and Direct Numeric Simulation (DNS) because of LES and DNS are more expensive and harder to apply for this model than RANS [10]. For the RANS simulation, FloEFD program is chosen. FloEFD is based on finite volume method. During the turbulence solution, FloEFD uses Favre-Averaged Navier Stokes equations with the k-ε model. For the Standard k-ε model, convection equations are given below:

For turbulence kinetic energy k is given equation 1 below.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_K+P_b+\rho\varepsilon-Y_M+S_k \qquad [1]$$

For turbulence dissipation rate ε is given equation 2 below.

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C1_\varepsilon\frac{\varepsilon}{k}(P_{k+}C_{3\varepsilon}P_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \qquad [2]$$

In the equations 1 and 2, ρ represents density, u, μ velocity and viscosity respectively. P_K represents creation of the kinetic energy due to average velocity gradients, P_b represents creation of the kinetic energy due to bouncy force, Y_M represents energy loss. $C1_\varepsilon$ and $C_{2\varepsilon}$ are constant, S_k and S_ε are the source term defined by users [11].

The simplified oven model is used during CFD analysis. To decrease number of mesh and avoid restricted edge border, original oven model is changed with the simpler model. As shown in the figure X, oven cavity is wrapped with the insulation material. Inside of the oven, fan, heater, fan baffle and tray are used. After creating the model, internal flow domain is chosen for this CFD study. In that section, Conduction is selected to be able to give wall heat transfer loss rate, gravity is selected to natural convection and rotation is selected for the fan modelling as a moving reference frame. As a fluid, only air is selected. CFD boundary and analysis conditions are shown in Table 2 below.

Table 2: Analysis Properties

Analysis Properties	**Selected Conditions**
Analysis Type	Internal
Physical Features_2	Conduction
Physical Features_1	Rotation
Fluid Material	Air
Solid Material	Insulation/Steel
Flow Type	Laminar and Turbulent

After analysis properties selection, boundary conditions are described. For simplified model, oven outer sheets are eliminated. In the set-up step, boundary conditions are specified. As a heat source, ring heater is chosen with the surface temperature method. Surface temperature of ring heater is measured with experimental study. For the fluid flow with convection method, cavity fan is used with the rotating region method which RPM is measured with experimental study. All boundary conditions are shown in Table 3 below.

Table 3: Boundary Conditions

Boundary Conditions	**Values**
Ring Heater Surface Temperature	610 ℃
Fan Rotation	1800 RPM
Air Temp	25℃
Air Pressure	101,325 kPa
Outer Wall Thermal Loss	5 W/m^2K
Door Thermal Loss	13 W/m^2K

3 types of material are used in this study. As a fluid material, air is used, as a solid, for the cavity and fan baffle material steel is used, for the insulation material needle glass wool is used. Thermal properties of materials are given in Table 4 below.

Table 4: Material Properties

Material	Thermal Conductivity $[W/mK]$	Specific Heat $[J/kgK]$	Density $[kg/m^3]$
Air	From library table	From library table	From library table
Steel	52	470	7800
Glass Wool	0.035	1250	33

As a mesh grids, “Cartesian Mesh” is used [9]. This mesh type is the default mesh in FloEFD. For the internal body, resolution level was 6, in the boundary area, resolution is 7. Also, for the rotating region, cylindrical mesh is used specifically. Total number of the mesh is 4,782,356 for this study.

3.Results

In this research, Type 0 which is the base baffle is tested experimentally first. Then CFD study is applied on Type 0 to verify the CFD method. After the validation, for the Type 3, 6,13 and 14, CFD analysis are run. Based on the CFD results, Type 6 is chosen to test experimentally to compare Type 0. Type 0 experimental and CFD results are shown in Table 5 below.

Table 5: Type 0 Cooking Experimental & CFD Results

Type	**TYPE0**		
Point Temp	**Experimental**	**CFD**	**Delta**
P1 [°C]	149.04	176.91	16%
P2 [°C]	147.18	176.80	17%
P3 [°C]	147.36	175.30	16%
P4 [°C]	144.42	176.13	18%
P5 [°C]	150.13	177.02	15%
P6 [°C]	149.01	176.94	16%
P7 [°C]	147.96	175.88	16%
P8 [°C]	147.79	176.18	16%
P9 [°C]	152.06	178.21	15%
P10 [°C]	149.92	176.87	15%
P11 [°C]	148.77	173.11	14%
P12 [°C]	149.30	175.42	15%
P13 [°C]	153.04	174.16	12%
P14 [°C]	152.08	175.22	13%
P15 [°C]	151.76	171.61	12%
P16 [°C]	150.97	172.77	13%
Max Temp [°C]	153.04	178.21	14%
Min Temp [°C]	144.42	171.61	16%
Average Temp [°C]	149.42	175.53	15%
Model Error			**15%**
Standard Deviation	2.244706273	1.797901	

As shown in Table 5 above, there are 15 % differences between experimental and CFD results averagely for measurement points on cooking tray inside oven. Based on these results, For the other baffle types are studied with CFD analysis. Results are shown in Figure 7,8 and Table 6 below.

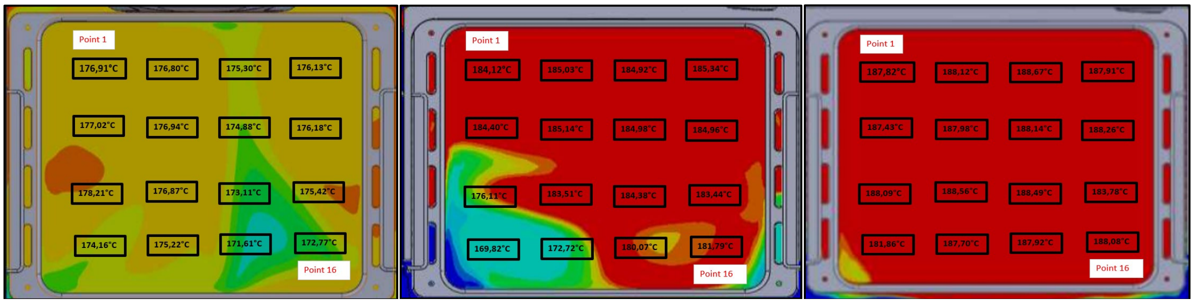

Figure. 7: Type 0, 3 and 6 Temperature Map on Tray

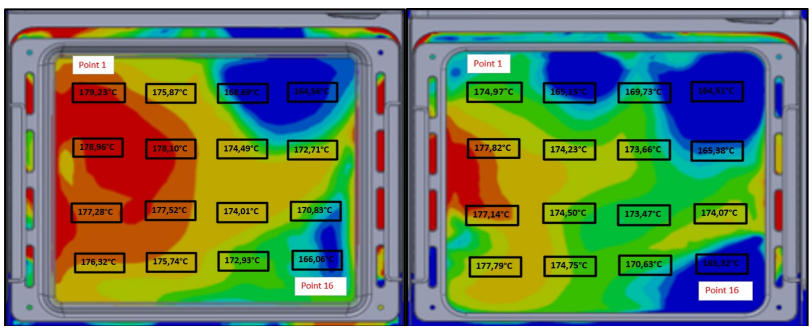

Figure. 8: Type 13 and 14 Temperature Map on Tray

Table 6: Baffle Types CFD Results

Tray Position	TYPE0	TYPE3	TYPE6	TYPE13	TYPE14
P1 [°C]	176.91	184.12	187.82	179.23	174.97
P2 [°C]	176.80	185.03	188.12	175.87	165.13
P3 [°C]	175.30	184.92	188.67	168.69	169.73
P4 [°C]	176.13	185.34	187.91	164.56	164.51
P5 [°C]	177.02	184.40	187.43	178.96	177.82
P6 [°C]	176.94	185.14	187.98	178.10	174.23
P7 [°C]	175.88	184.98	188.14	174.49	173.66
P8 [°C]	176.18	184.96	188.26	172.71	165.38
P9 [°C]	178.21	176.11	188.09	177.28	177.14
P10 [°C]	176.87	183.51	188.56	177.52	174.50
P11 [°C]	173.11	184.38	188.49	174.01	173.47
P12 [°C]	175.42	183.44	187.78	170.83	174.07
P13 [°C]	174.16	169.82	183.86	176.32	177.79
P14 [°C]	175.22	172.72	187.70	175.74	174.75
P15 [°C]	171.61	180.07	187.92	172.93	170.63

P16 [°C]	172.77	181.79	188.08	166.06	165.32
Max Temp [°C]	178.21	185.34	188.67	179.23	177.82
Min Temp [°C]	171.61	169.82	183.86	164.56	164.51
Average Temp [°C]	175.53	181.92	187.80	173.96	172.07
Standard Deviation	**1.80**	**4.83**	**1.10**	**4.45**	**4.69**

All point temperatures are taken 29mm above the interior bottom side of the tray according to thermocouples which used in Type 0 experimental test. As shown in the CFD results above, Type 6 has the lowest standard deviation between measurement points on cooking tray in the middle of the oven so that Type is selected to crease physical baffle sample to apply tested experimentally to compare with Type 0. Air flow vector distribution of Type 6 is shown Figure 9 below.

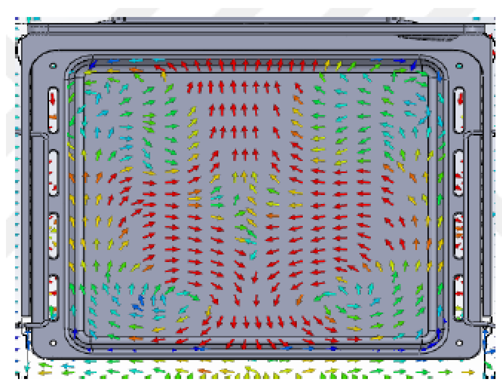

Figure. 9: Type 6 Air Flow Vector Distribution

As a last step of this study, Type 6 baffle is produced as a sample and tested experimentally to compare original baffle. Results are shown in Table 7 below.

Table 7: Experimental Comparison between Type 0 & Type 6

Tray Position	TYPE0	TYPE6
P1 [°C]	149.04	158.48
P2 [°C]	147.18	159.36
P3 [°C]	147.36	159.24
P4 [°C]	144.42	159.22
P5 [°C]	150.13	156.00
P6 [°C]	149.01	155.93
P7 [°C]	147.96	156.22
P8 [°C]	147.79	157.09
P9 [°C]	152.06	154.99
P10 [°C]	149.92	153.69
P11 [°C]	148.77	154.47
P12 [°C]	149.30	155.70
P13 [°C]	153.04	153.53
P14 [°C]	152.08	153.41
P15 [°C]	151.76	153.78

P16 [°C]	150.97	153.49
Max Temp [°C]	153.04	159.36
Min Temp [°C]	144.42	153.41
Average Temp [°C]	149.42	155.91
Standard Deviation	**2.24**	**2.19**
Delta to Set Temp. [°C]	**10.58**	**4.09**
Delta Max – Min Temp [°C]	**8.62**	**5.95**

As a summary of the results in this research, as a first step with the original baffle which is Type 0, cooking performance test simulation is created by experimentally. There are 16 thermocouples are used inside of oven on middle tray. All thermocouples are positioned according to cake position which is 29mm above from interior-bottom side of tray. Physically cakes are not used in this experimental study to avoid apply mass transfer during CFD study to decrease model error. Then, Type 0 CFD study is run to obtain model error on CFD study. There is 15% difference between experimental and CFD study for each measurement points averagely. This difference is coming because of neglecting points like radiation heat transfer, simplifications on model, heat bridges of oven structure. By accepting this difference between experiment and CFD calculation, other baffle types are tried on CFD study. Type 6 has the lowest standard deviation and highest temperatures as an advantage of cooking time. As a last step of this study, Type 6 is tested experimentally and compared with Type 0. With this improvement, better cooking performance results are obtained.

4. Conclusion

Main target of this study is to find the most optimized baffle type for related built-in oven. By validating of CFD methods, different baffle types are tried with the CFD simulation and evaluation of results show that Baffle Type 6 has the better cooking performance than other baffle types by calculating 16 points temperatures, standard deviation between each temperature of measurement points, delta between set of the oven temperature and average temperature of all points, and delta temperature between maximum value and minimum value among all temperatures of each type.

Acknowledgements

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