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Effects of insulation parameters on the energy consumption in domestic ovens and the most efficient insulation design

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Abstract. Studying on insulation and its parameters has some difficulties comparing to the other factors which affect energy consumption. On the other hand, not only computational studies, but also experimental studies are important in understanding the heat and fluid flow in domestic ovens. By having knowledge on how insulation parameters effect on the energy consumption, getting efficient designs will come through easily. This study focuses on deciding optimum insulation design, by decreasing thermal bridges over itself. Firstly, experiments are performed for determining excessive heat region on a reference oven's insulation. Also these experiments are completed with two different thermocouple layouts in various temperatures and isotherm maps are generated for inner and outer chassis surfaces. Reference oven's insulation is also scanned by thermal camera. The results of overheated areas and thermal camera images are compared with each other. Different insulation designs are devised on the comparison of the conclusions. Standard energy consumption experiments are performed for each insulation designs under the working mode, which the dominant one in heat transfer, is forced convection. The most efficient insulation was scanned again by thermal camera and these thermal images showed that it decreased overheated areas on outer chassis surface. The experimental studies showed that energy consumption of the domestic oven decreased 4.5% with the new insulation design.

1. Introduction

Energy consumption is increasing rapidly over the world and energy price also going up day to day. Because of that, both manufacturers and consumers are focusing on home appliances with low energy consumption.

Therefore, studies are accelerated on these devices. Over the last 10 years, these devices have very common usage. First, the European Union (EU), commenced work in accordance with these studies and the EU Commission issued a directive for electric ovens for household use.

In domestic ovens, there are lots of parameters that affect energy consumption. Insulation and thermal bridges on insulation are main parameters for energy consumption. Basically, insulation is used in oven door window, connecters, around of cooking chamber and back side of the oven on which electronic parts take place. Connecters and electronic parts create thermal bridges which are increasing energy consumption of domestic ovens.

Maitenaz and Gernez [1] designed such an oven cavity that positions of the heaters and the insulation ensured minimum amount of heat loss and very few thermal bridges. Their definitions are secured by patent

European Committee for Electrotechnical Standardization (CENELEC) standardized the safety range of oven case temperature. Thus, of the role of insulation is both improving the heat resistance and keeping temperature under safety range to prevent the heat loss through the case. Therefore, CENELEC underlines that studies to prevent heat loss in the oven are important to determine minimum heat loss to the outside [2].

Scarisbrick, Newborough and Probert [3] investigated on improving oven's thermal performance by trying different insulation parameters. Cooking time, energy consumption and the state of the case temperature are examined by trying out different combinations. In that study, firstly they performed an experimental study on the oven itself by removing the insulation materials and by that they determined reference energy consumption of their oven. Second, they work without insulation and just only used aluminum foil to see effects of radiation. After that, they have replaced aluminum foil with 50 mm glass wool to oven's case and analyzed energy consumption again. Finally, they changed insulation material with 25 mm Microtherm®, which has better thermal resistance comparing to the glass wool, with aluminum foil just over the oven's case. Table 1 shows experimental results of these combinations [3].

Table 1. Experimental results of Scarisbrick, Newborough and Probert [3]

Insulation Design	Energy Cons. k W h	Thermal Resist. $m^2K\ W^{-1}$	CaseTemp.
None	2.01	0	Over the standards
Only Aluminum Foil	1.30	0.30	Over the standards
50 mm Rockwool Glass Wool	0.82	0.78	20 0C Less than Reference
25 mm Microtherm and Aluminum Foil	0.73	1	30 °C Less than Reference

Bozgeyik studied energy consumption by measurements due to the different thicknesses of insulation material. Also, this study shows that the energy consumption is improved depending on thicknesses of glass wool and rock wool. In addition, energy consumption difference between almost the same thicknesses of glass wool and ceramic wool is more than the other materials. This result is due to the density of ceramic wool which is higher than both glass wool and rock wool. Thus, with usage of ceramic wool thermal inertia of oven is increased [4].

Miele® Company designed an alternative insulation material with aerogel material and they secured this design by patent in 1992. Aerogel insulation material has different forms so it is used in oven's case and door window [5].

Hancilar analyzed the current state of the oven, the structure of the front cover, oven insulation and infiltration losses in details. Hancilar [6] also concluded that since the oven reaches high temperature values, heat conduction coefficient, which is effective on energy consumption, should not change significantly. Depending on temperature, heat conduction coefficient is shown in Table 2.

Table 2. Thermal conductivity due to the temperature increase [6]

	Glass Wool	
Density ($kg\ m^{-3}$)	32	
Heat Capacity ($J\ kg^{-1}\ K^{-1}$)	1030	
Thermal Conduction Coefficient [$W\ m^{-1}\ K^{-1}$]	Temp.	k
	100	0.041
	200	0.055
	300	0.072
	400	0.092
	500	0.118

In this study, as a priority in terms of investigating the heat transfer, spatial and transient temperature distributions are obtained for each surface of the oven. The temperature values from each surface were taken by repeating experiments. After that, deviation of experimental results is calculated. This aspect in fact is analyzed in terms of experimental repeatability and consistency. In addition, these initiator experiments give how many measurement points are enough to obtain stable and consistent experimental results. To do that, these temperature values are put on the computer and a third degree interpolation has been made. Finally, all of this information used in determining the insulation material to be used, the location and application on the oven.

Other part of this study aims to get temperature values on measurement surfaces by thermal camera and comparing these experimental results with the ones that are acquired by thermocouples. Redesign of insulation is mainly based on thermal image and determining most effective insulation.

2. Experimental Setup

Experiments were performed with 65 liter volume of domestic oven at the High Temperature Heat

Transfer Laboratory of Mechanical Engineering Department of Istanbul Technical University, Turkey. To perform the experimental study, Hipor brick, which is also moisture source, is used in order to resemble the cooking process in the oven. That process is also standardized by CENELEC with EN 50304.

2.1 Pre-Experiments of the Study

Before making changes on the oven, the reference oven characteristic was examined by applying the same experiments. The importance of these experiments is the fact that it provides an objective approach to assess the results of other experiments. In order to minimize the error, reference measurement experiments repeated two times for each operating temperatures[1]. These pre-experiments show the overheated regions and where could be the thermal bridges observed. Figure 1 shows the back side of the oven, electronic parts, connecters and potential thermal bridge areas on that surface. As can be seen from Figure 1, there are possible eight thermal bridges detected.

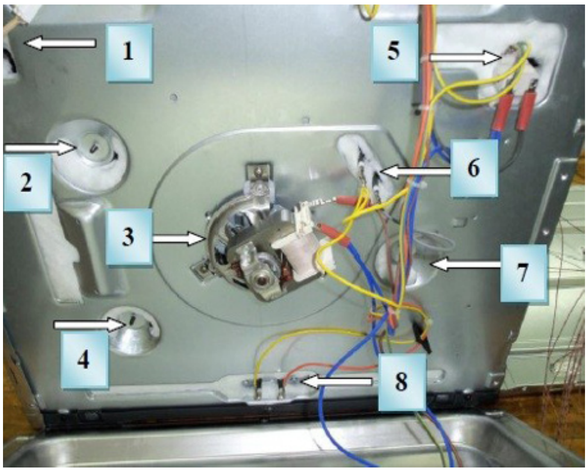

Fig. 1. Back side and the thermal bridges

2.2 Insulation Materials

Choosing insulation materials has crucial importance for thermal insulation tests. There are some properties desired from insulation materials which are high density, to be fireproof, low heat capacity and thermal conductivity. Considering the main features of these, insulation materials which can be used in ovens are investigated. Both in literature and as well as applied, glass wool and aerogel are the insulation materials of this study. Additionally, hybrid-insulation designs which are the combinations of insulation materials with each other have also been tried.

[1] Operating temperature is the temperature which is measured at the center of the cavity.

2.3 Layout Independency

Before starting experiments to test the parameters of the insulation, "Thermocouple Layout Independency Study" experiments were carried out to obtain the data from all insulation that surrounds the cavity. The purpose of these experiments is to generate the isothermal maps of the oven. Therefore, critical regions can be determined by experimental results and insulation design can be generated rightly.

Nine thermocouples, as shown in Figure 2, were placed at the bottom of the insulation which contact with the external surfaces of the case, while the other nine thermocouples were placed at the same direction inside of the cover. The duration of the experiments is determined by five temperature cycles after the first highest temperature of the oven's center.

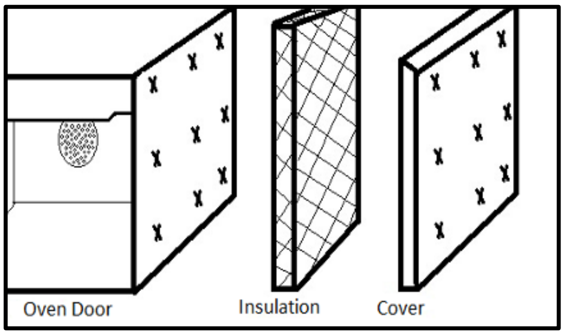

Fig. 2. Thermocouple layout

In addition, experiments with nine thermocouples have been expanded with nine thermocouples for each line of surfaces showed in Figure 3. That means that there were twenty-seven thermocouples for each surface. It provides to gather detailed temperature data. Therefore, isothermal maps become smoother in comparison to the ones obtained by the layout with nine thermocouples.

Fig. 3. Array of Nine Thermocouples for Detailed Isothermal Map

In order to analyze these data obtained from the experiments, temperature vs. time graphics were generated for each surface. In addition, isothermal maps were generated to determine temperature distribution on each surface. These maps are obtained from average temperature of each point with third degree interpolation.

2.4 Different Insulation Designs

To decrease the energy consumption, different insulation designs were generated with chosen materials. All designs are tried to close all the holes like shown in Figure 1 to decrease thermal bridges. There are three different new insulation designs which are:

- Design 1: All sides with 30 mm glass wool,
- Design 2: All sides with 20 mm aerogel,
- Design 3: 20 mm glass wool in contact with the sides of the case and 20 mm aerogel on glass wool.

These new designs used in the critical regions where pre-experiments were pointed out. Also all three designs were experimented at three different (160^{0}C/180^{0}C/200^{0}C) operating temperatures.

2.5 Thermal Camera

To get thermal camera images, surface color should be black in order to prevent reflecting light back to the camera. Therefore, while getting images, outer surface of the oven coloring with matte black spray. Also, distance of the camera and surface, should be determined and angle has to be 90 degree of each other to have correct results.

3. Mathematical Model

Under some assumptions and simplifications, partial differential equation, which governs heat transfer in solid bodies are, reduced to an ordinary differential equation (Eqn. 3.1). It must be also noted that, quasi-steady state assumption should be made for each temporal measurement step. Hence, it is necessary that the results of the experiments should be related to a mathematical model. Therefore, calculation of the amount of heat loss from the insulation becomes important for comparing the energy consumption of each design. To do that, for the condition of no heat generation in the wall for a continuous regime conditions, the heat transfer equation is written,

$$\frac{\mathrm{d}}{\mathrm{dx}}\left(\mathrm{k}\frac{\mathrm{dT}}{\mathrm{dx}}\right) = 0 \tag{3.1}$$

In this equation, acceptance of these boundary conditions which are, x = 0 and x = L, so,

$$T_0 = T_i \text{ and } T(L) = T_d \tag{3.2}$$

If condition 3.2 put in 3.1, temperature distribution would be,

$$T(x) = (T_d - T_i)\frac{x}{L} + T_i \tag{3.3}$$

As a result of that, for no heat generation and constant thermal conductivity, the temperature is varied linearly with x direction. Thus, heat transfer can be found by Fourier's Law;

$$q_x = -kA\frac{dT}{dx} = \frac{kA}{L}(T_{,} - T_d) \tag{3.4}$$

T_i	Temperature on the inside surface of the insulation [^{0}C]
T_o	Temperature on the outside surface of the insulation [^{0}C]
A	Area of the surface [m^2]
L	Length of insulation [m]
k	Thermal conductivity [W m^{-1} K^{-1}]
q_x	The heat transfer per unit time per length [W m^{-1}]

Part of these variables has been obtained from the experiments and part of them has been known, already. Putting data into the equation (Eqn. 3.1) and after finding the heat transfer they are compared with the energy consumptions of the experiments.

4. Results and Discussion

Figure 4 shows isothermal maps of oven based on the experimental data. It is seen that the critical sides are outside surfaces of the insulation. Also left and right sides of the oven have almost symmetrical temperature maps. However, back surface of the oven is warmer than the sides. There is about 30-40 °C temperature difference between these surfaces because of the electronic parts and insulation gaps which cause more thermal bridges on that surface.

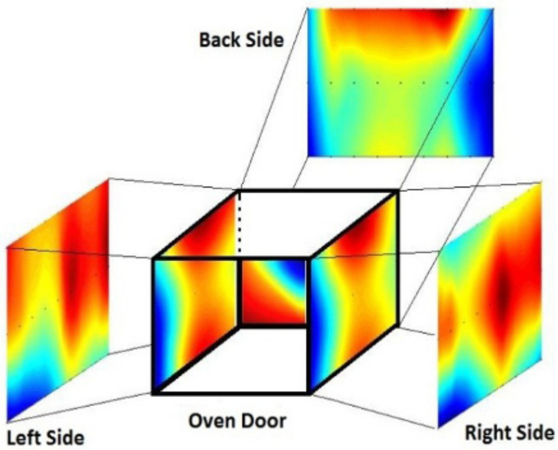

Fig. 4. Isothermal maps of the oven surfaces

4.1 Discussion of the Temperature – Time Graphs

Standard deviations of cavity center temperature in five cycles were analyzed to observe temperature – time graphics. Due to the variable cycle oscillations and maximum temperature values, the evaluation of these statistical details is necessary.

As can be seen in Table 3, the highest temperatures were almost the same in different experiments. However, standard deviation of cycle (σ_{cyc}) oscillations was variable. Because of that, heaters are activated in different periods of each experiment. This condition caused unstable temperatures in outside of the oven cavity and heat losses from insulation.

Table 3. Standard deviation of temperatures collected from the surfaces

Experiment Location	Standard Deviation of Cycle (σ_{cyc})		
Right Side	2.854		
Left Side	Exp.1 3.891	Exp.2 3.575	
Right and Left Side (Detailed)	Layout1 3.097	Layout2 3.445	Layout3 3.642
Back Side	3.868		
Back Side (Detailed)	Layout1 3.411	Layout2 3.562	Layout3 3.745

4.2 Comparison between Isothermal Maps and Thermal Camera Images

As it is seen from Figure 5 and 6, there are some differences between two layouts. One of these, maximum temperature of surface is occurred at point (3,9 See Fig. 2) in nine thermocouples layout. However in twenty-seven thermocouple layout, it is at point (6,6 See Fig. 2).

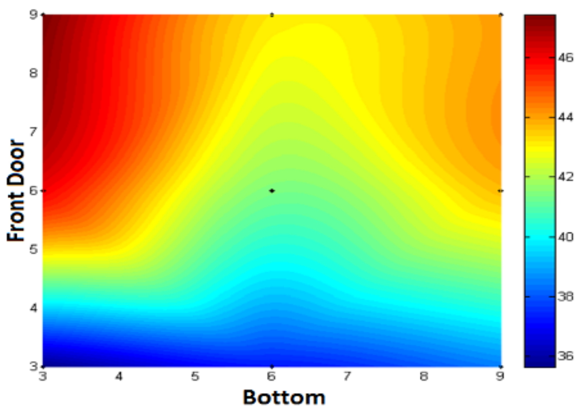

Fig. 5. Right Surface – Temperature Distribution on the Insulation

Because of this dissimilarity situation, oven surfaces need to be scanned by thermal camera to see which layout represents more accurate distribution.

As it seen, temperature distribution in details (Figure 6) is almost the same with thermal camera image illustrated in Figure 7. Therefore, as much as the temperature data taken from the surfaces, better results are available from the isothermal maps.

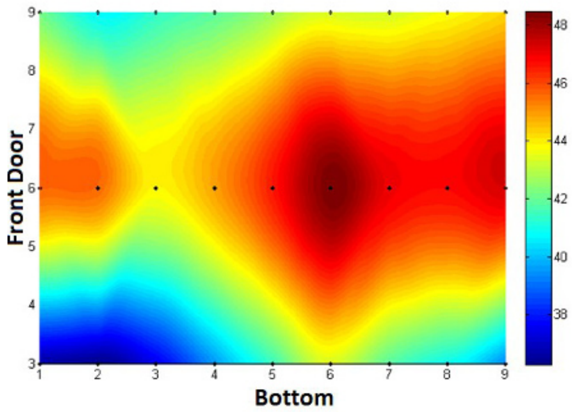

Fig. 6. Right Surface – Temperature Distribution on Insulation in Details

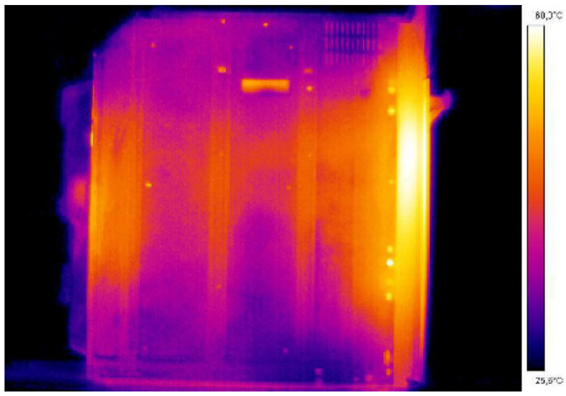

Fig. 7. Thermal Camera Images taken on the Right Surface

When the back of oven is investigated, it is seen that this area has much more complicated results comparing to the side surfaces. First of all, connecters, fan and the other electronic parts are behaving as a thermal bridge as seen in Figure 8 (See also Fig. 1).

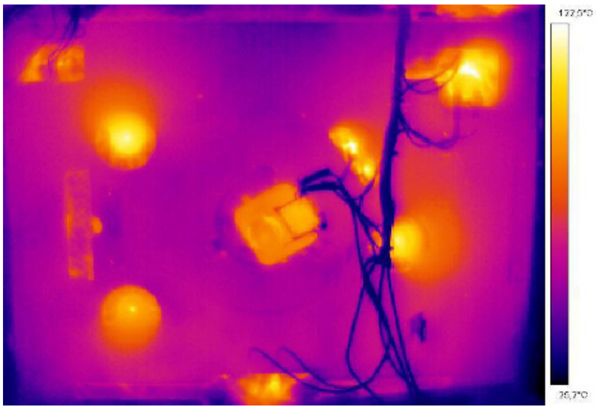

Fig. 8. Thermal Camera Image taken on the Back Surface

Temperature of these thermal bridges rises almost to 120°C. That means that with suitable design of the back side, these holes could be closed and energy consumption can be decreased. Especially fan area is the critical one comparing to the others.

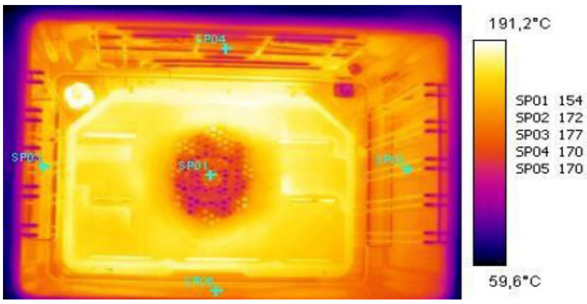

Fig. 9. Thermal Camera Image of Cavity, Heater and Fan

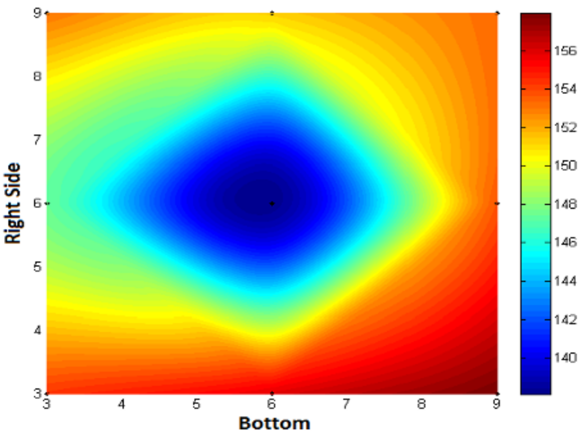

Fig. 10. Back Surface – Temperature Distribution under Insulation – Fan Area

Figure 9 shows that, temperature values on the surfaces reach over 175°C. However, fan temperature is lower about 20°C from all other surfaces. That means, heat is leaving from the fan area to the outside. Thus, when Figure 10 is analyzed, fan area is the coldest one of the back surface. The thermal appearance of the region around the fan is consistent with the predictions prior to the experiments.

4.3 Analysis of New Insulation Design

4.3.1 Analysis of insulation designs at 160°C forced convection temperature mode

Energy consumptions of different designs at 160°C turbo-mode are presented in Table 4. In this way, comparisons can be made between designs, easily. First design has the lowest energy consumption according to the results. The highest energy consumption has been obtained as a result of the changes made in Design 2.

Table 4. Energy consumption of 160°C turbo-mode

	Energy Cons. (W h)	% Change According to Reference
Reference	747	-
Design 1	**727**	**-2.68**
Design 2	835	11.78
Design 3	752	0.67

4.3.2 Analysis of insulation designs at 180°C forced convection temperature mode

Energy consumptions of these designs at 180°C turbo-mode are presented in Table 5. The Design 1 results in the lowest energy consumption. On the other hand, highest energy consumption has been obtained as a result of the changes made in Design 2.

Table 5. Energy consumption of 180°C turbo-mode

	Energy Cons. (W h)	% Change According to Reference
Reference	815	-
Design 1	**778**	**-4.54**
Design 2	881	8.09
Design 3	836	2.58

4.3.3 Analysis of insulation design at 200°C forced convection temperature mode

Energy consumption of design options at 200°C turbo-mode are presented in Table 6. Design 1 has lowest energy consumption again. Design 2 has highest energy consumption again for this mode. That must be considered about Design 3 is, thermal conductivity of the insulation materials rises while operating temperature increases.

Table 6. Energy consumption of 200°C turbo-mode

	Energy Consumption (W h)	Change According to Reference, %
Reference	875	-
Design 1	**848**	**-3.09**
Design 2	953	8.91
Design 3	889	1.6

4.4 Results of the Mathematical Calculations

A calculation of heat losses for all experiments and surfaces are shown in Tables 7, 8 and 9.

Table 7. Preheating Time, Energy and Total Heat Loss at 160°C turbo-mode

160°C Operating Temp.			
	Preheating Time	**Preheating Energy**	**Heat Loss**
Units	**Min.**	**W h**	**W h**
Reference	7.25	219	-
Design 1	7.64	227	156.5
Design 2	11.41	340	153.9
Design 3	10.99	323	145.9

Table 8. Preheating Time, Energy and Total Heat Loss at 160°C turbo-mode

180°C Operating Temp.			
	Preheating Time	**Preheating Energy**	**Heat Loss**
Units	**Min**	**W h**	**W h**
Reference	9.28	286	-
Design 1	9.76	295	182.6
Design 2	14.12	418	178.9
Design 3	13.62	399	170.6

These heat losses point that, increase of the operating temperature also increases the heat loss. However, another reason of these increases is the process of preheating. Disorder between heat loss and preheating energy is thought that algorithm of the preheating process needs to be optimized.

Table 9. Preheating Time, Energy and Total Heat Loss of 160°C turbo-mode

200°C Operating Temp.			
	Preheating Time	**Preheating Energy**	**Heat Loss**
Units	**Min**	**W h**	**W h**
Reference	11.12	337	-
Design 1	12.09	361	204.9
Design 2	16.67	499	203.8
Design 3	16.55	485	179.6

4.5 Economical Analyze

8% of the household appliances, which is 5.5 million totally, in Turkey, are built-in products. This rate will be expected 10% in later years [7]. In this study, Design 1 has no more insulation materials compared to the reference insulation. Thus, economically Design 1 has no extra-spending at all.

5. Conclusion and Suggestions

Most of the energy consumption passes to the oven's components (thermal mass) by the conduction mechanism. During the preheating of the available volume, components, which are basis of thermal mass, reach a certain saturation point during on-off cycles. The effect of insulation in enclosures should not be underestimated in order to keep the heat in the center of the cavity. In this way, when cooking is the main task, consumed energy would be directed to the cavity by improving on the insulation material, changing the insulation thickness or density.

Heat loss did not change directly proportional to energy consumption, as a result of mathematical analysis. Radiation heat transfer and construction of the enclosure should be taken into consideration in order to compare the heat loss and energy consumption under the same conditions.

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