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Energy consumption analysis of domestic oven

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Abstract

For cookers with oven to be interesting for the market, they need to exhibit a high energy efficiency. On the basis of an analysis of individual influences on the energy efficiency of ovens, several solutions were proposed for improving oven operation. An analytical solution was made for describing the nonstationary temperature field within a test brick with convection at a constant heat transfer coefficient and a continuously variable temperature of the surrounding fluid using Green's functions. The influences of door sealing, vapor outlet slit, additional insulation, the oven regulation regime, door glazing and irradiation within the oven were experimentally analyzed. Because of the proposed improvements, the analyzed mass produced oven was moved to the A class of energy efficiency according to standard EN 50304:2001.

Introduction

Kitchen ovens consume large amounts of energy in households. By increasing their energy efficiency, it is possible to reduce greenhouse gas emissions via reduction of energy consumption. The energy efficiency of ovens is marked on energy labels. Oven manufacturers are increasingly forced to adjust their products to market requirements by developing ever more energy efficient ovens that fulfill Class A criteria [1-3]. Functionality, design and energy efficiency all need to be taken into account [4-6].

Standard EN 50304:2001 [7] prescribes measurement of energy consumption after the oven is switched on and once a Hipor test brick saturated with moisture is heated from 5 to 55 ^{o}C. Depending on the oven size, the electrical energy consumption in the given case should be below 800 Wh in conditions of natural air convection without the fan, or forced air convection with the oven fan switched on.

This paper focuses primarily on an experimental theoretical analysis of individual influential parameters that affect the energy efficiency of mass produced ovens.

Modeling of heat transfer within the oven

In order to be able to improve the energy efficiency of an oven, one must analyze the influence of the greatest possible number of parameters that affect it. However, a numerical approach in the form of 3D oven modeling does not enable the analysis of a greater number of parameters because of its complexity. Since the standard for determining the energy efficiency prescribes measurement of consumed energy for the required increase in the temperature inside a moist test brick while it is heated in the oven, we decided to approach the description of the nonstationary temperature field in the test brick analytically.

Fourier's equation for heat convection

$$\frac{\partial^2 T}{\partial x^2} + \frac{g(x,t)}{\lambda} = \frac{1}{a}\frac{\partial T}{\partial t} \qquad (1)$$

was solved analytically for a plate using Green's function (general solution) [1]:

$$T(x,t) = \int_{x'=0}^{L} G(x,t|x',0)F(x')\cdot dx' + a\sum_{i=1}^{s}\left[\frac{(\rho cL)_i}{\lambda_i} G(x,t|x',0)F(x')\right]_{x'=x_i} + \int_{\tau=0}^{t}\int_{x'=0}^{L}\frac{a}{\lambda}G(x,t|x',\tau)g(x',\tau)\cdot dx'\cdot d\tau + $$
$$+ a\int_{\tau=0}^{t} d\tau\sum_{i=1}^{s}\left[\left(\frac{f_i(\tau)}{\lambda_i}G(x,t|x_i,\tau)\right)\right] - a\int_{\tau=0}^{t} d\tau\sum_{i=1}^{s}\left[f_i(\tau)\frac{\partial G}{\partial n_i'}\bigg|_{x'=x_i}\right] \qquad (2)$$

For the nonstationary continuous temperature variation of the surrounding fluid, we assumed that

$$T_\infty = \left(T_{\infty,maks} - T_{\infty,\infty}\right)\cdot\left(k_1\cdot e^{k_2\cdot t} + k_3\cdot e^{k_4\cdot t}\right) + T_{\infty,\infty} \qquad (3)$$

By using constants k1 through k4 under the following conditions:

$$k_1 > 0,\ k_2 > k_3,\ k_4 < k_2 < 0, \qquad (4)$$

it is possible to capture the variation of temperature with time as can be seen in Figure 1.

This can serve as the basis for analyzing processes in the oven.

The maximum temperature is expressed as

$$T_{\infty,maks} = \frac{T_{\infty,0} - T_{\infty,\infty}}{k_1 + k_3} + T_{\infty,\infty} \qquad (5)$$

Taking into account a constant heat transfer coefficient for heat transfer to the surrounding fluid and variable ambient temperatures according to equation (3), the nonstationary temperature field of a semiendless plate is in the form:

$$T(x,t) = 2\cdot T_0\cdot\sum_{m=1}^{\infty} e^{-\frac{\beta_m^2 at}{L^2}}\cdot\frac{\sin\beta_m}{\beta_m + \sin\beta_m\cdot\cos\beta_m}\cdot\cos\left[\beta_m\left(\frac{x}{L}\right)\right] + \sum_{m=1}^{\infty}\frac{4k_1 aL\alpha\beta_m\left(T_{\infty,maks} - T_{\infty,\infty}\right)\cdot\cos\left[\beta_m\left(\frac{x}{L}\right)\right]\cdot\cos\beta_m}{\lambda\left(k_2L^2 + \beta_m^2 a\right)\cdot\left(2\beta_m + \sin(2\beta_m)\right)}\cdot\left(e^{k_2 t} - e^{-\frac{\beta_m^2 at}{L^2}}\right) +$$
$$+\sum_{m=1}^{\infty}\frac{4k_3 aL\alpha\beta_m\left(T_{\infty,maks} - T_{\infty,\infty}\right)\cdot\cos\left[\beta_m\left(\frac{x}{L}\right)\right]\cdot\cos\beta_m}{\lambda\left(k_4L^2 + \beta_m^2 a\right)\cdot\left(2\beta_m + \sin(2\beta_m)\right)}\cdot\left(e^{k_4 t} - e^{-\frac{\beta_m^2 at}{L^2}}\right) + \frac{4\alpha L}{\lambda}T_{\infty,\infty}\sum_{m=1}^{\infty}\frac{\cos\left[\beta_m\left(\frac{x}{L}\right)\right]\cdot\cos\beta_m}{2\beta_m^2 + \beta_m\sin(2\beta_m)}\cdot\left(1 - e^{-\frac{\beta_m^2 at}{L^2}}\right) \qquad (6)$$

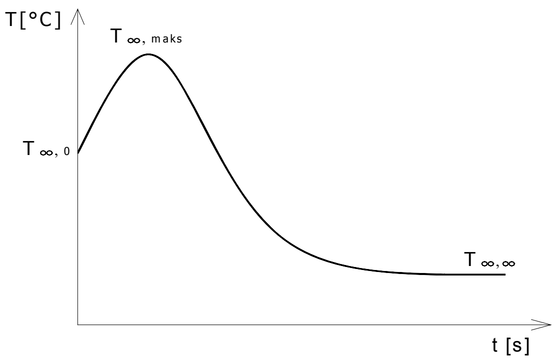

Figure 1 Example of variation of the surrounding fluid's temperature with time.

In order to determine the nonstationary temperature variation in a three-dimensional brick, the principle of superposition is used.

Experimental set up and test procedure

Figure 2 shows two cooker models that were used to perform oven measurements, namely Gorenje Pininfarina and Gorenje E774W. The model Gorenje E774W had an oven insulated with glass wool with a thickness of 3 cm, and Pininfarina had glass wool with a thickness of 5 cm. The oven door was double-glazed. Oven controls were set so as to allow temperature oscillations within the oven of about 10 K around the set temperature. When the oven operated with natural air convection only (switched off fan), two heaters were used – an upper and a lower one. During oven operation with forced air convection, the lower heater and the peripheral heater (which is installed around the fan) were switched on.

Figure 2 Gorenje E774W and Gorenje Pininfarina.

Figure 3 shows an oven schematic with the positions of the heaters and fan opening.

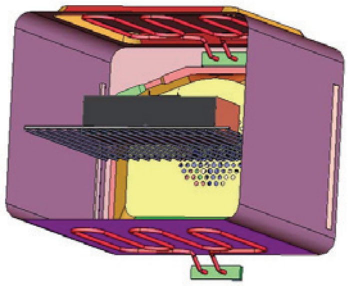

Figure 3 Schematic of oven in the Gorenje E774 W cooker.

The consumed energy was measured using a Siemens Simeas P power meter, which measures the input voltage and current, after which an integral processor calculates the desired values. The measurement accuracy of the power meter for the measurement of electric voltage and current is ±0.2 %, and for measuring power it is ±0.5 %.

The weight of the brick was measured using a Siemens Siwarex U balance. The balance was placed on top of the cooker. A bore with a diameter of 1 mm was drilled through the plate, insulation and the oven, and a thin wire was led through that connected the balance with a basket containing the test brick that was placed in the oven.

The temperature was measured using thermocouples Class 1 according to EN 60548-2 standard in a steel casing with an external diameter of 1 mm. The thermocouples were fit snugly inside the bores within the test brick. For all measurements according to standard EN 50304:2001, measurement of two temperatures is required. In our case, however, 10 were done to be able to analyze heat conduction within the test brick. A schematic of the measurement sites on the test brick and a picture of the thermocouples installed in the test brick are shown in Figure 4.

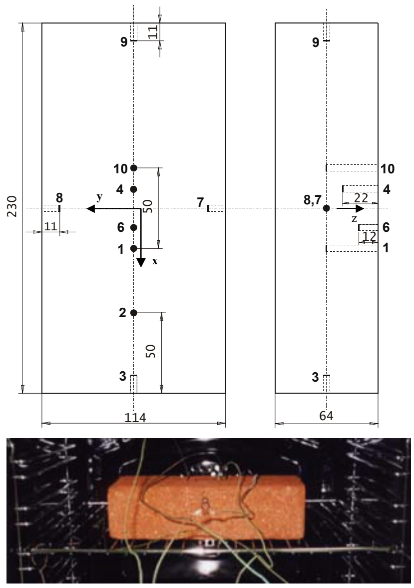

Figure 4 Measurement sites on Hipor test brick.

For the regulation of oven heaters, electronic elements were added to the oven with output relays for switching the heaters on, as well as power supply for external electronics that transformed the software PID controller data into an electric signal and sent it to the relays, which then switched oven heaters on or off. The PID controller was connected with the LABView PC program, via which the oven operation regime was determined for individual heaters and data were captured. The temperature profile was also set and it was determined which heaters should be switched on. Settings of the PID controller were also made.

The objective was to achieve Class A of energy efficiency for the oven according to standard EN 50304:2001. The standard for Class A prescribes that a Hipor test brick saturated with moisture should be heated from 5 to 55 ^{o}C after the NG 500 oven is switched on, whereby the total electrical energy consumption needs to be lower than 800 Wh, for both natural air convection and for forced air convection. A new test brick has to be dried in the oven before use for 3 hours with forced air circulation at a temperature of ≥175 °C. The weight of the dried brick without thermocouples has to be measured within 5 min after its removal from the oven. Then the brick can be used for up to 20 measurements to measure the time and consumed energy that is necessary for an empty oven to be heated from the ambient temperature by 180 K in the case of natural convective air circulation, or by 155 K in the case of forced air circulation with the use of a fan. Two thermocouples required by the standard are fitted into the test brick such that the measuring sites are in the center of the brick, and the distance between the thermocouples is 50 mm (marks 1 and 10 in Figure 4).

Results and discussion

Figure 5 shows the influence of the rate of heating of the surrounding air on the increase in brick surface temperature in the middle of the test brick, as an example of using equation (6).

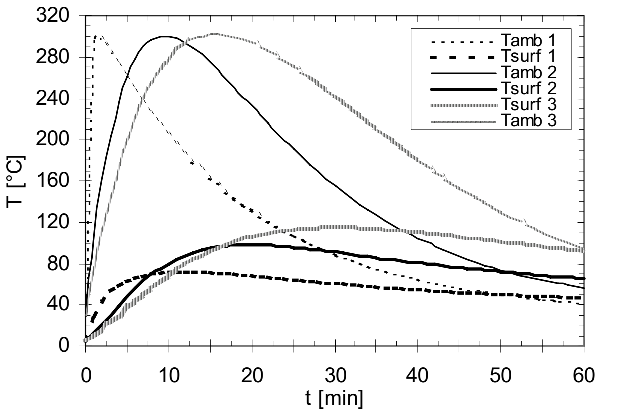

Figure 5 An example of using equation (6).

Figure 6 shows a comparison between the measured and calculated temperature curves during heating of dry brick at natural convection. The differences primarily resulted from inaccurate approximation of the temperature variation of the surrounding air, nonobservance of the irradiative share of heat transfer from the oven walls to the test brick, and a nonuniform initial temperature field in the test oven.

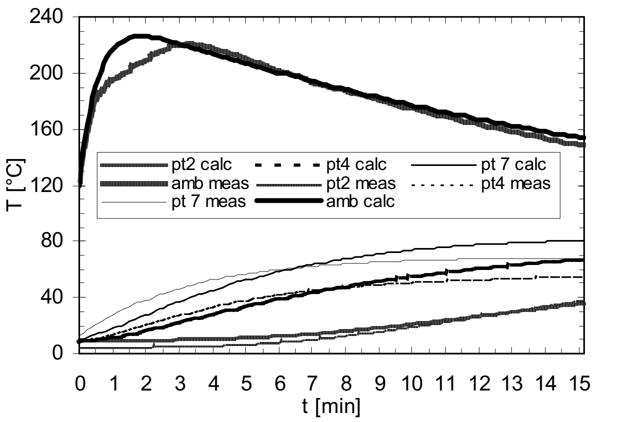

Figure 6 Comparison of the measured and calculated temperature profiles during heating of dry test brick at natural air convection, $\alpha = 16$ W/m^{2}K.

Infrared camera ThermaCam S60 manufactured by Flir was used for thermographic measurements. Figure 7 shows IR photographs of the test brick and Figure 8 the time variation of the mass of moist test brick during drying, while it is heated with forced air convection and overheated to 155 K.

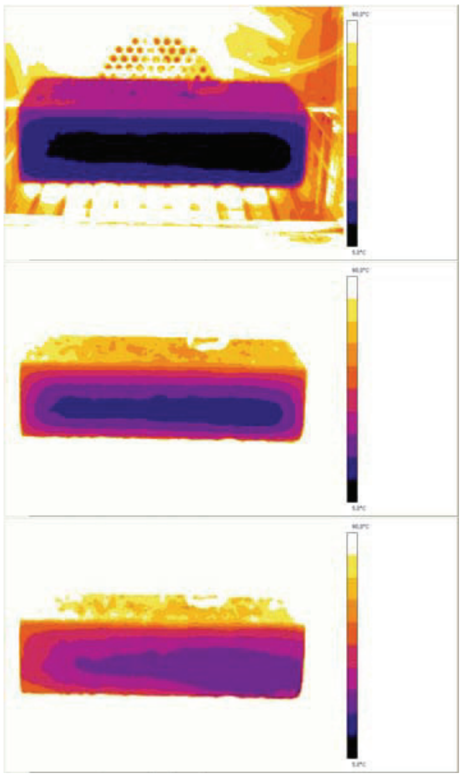

Figure 7 IR photographs of the test brick after 8, 16 and 32 min of heating with forced air convection and overheating of 155 K.

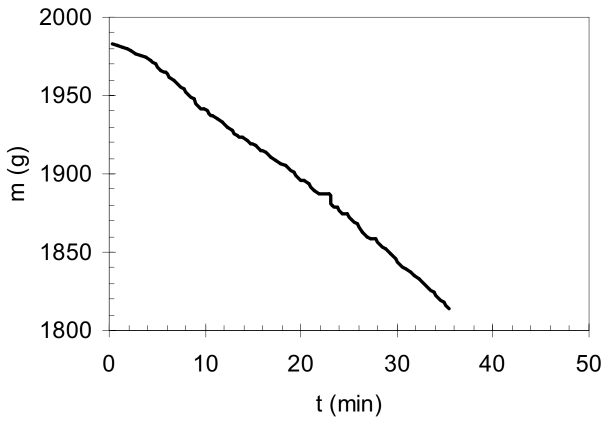

Figure 8 Time variation of the mass of moist test brick during heating with forced air convection with 155 K overheating.

The influences of sealing of the door, vapor outlet slit, additional insulation, the regulation regime, door glazing and irradiation in the oven were analyzed.

The sealing of door and gaps/slits on the oven was performed using an aluminum self-adhesive insulating tape. This measure reduced the energy consumption from the baseline of 917 Wh to 801 Wh.

The effect of the vapor outlet channel was tested by plugging the vapor outlet slit in addition to sealing all of the gaps and slits on the oven. After this, the oven's energy consumption decreased to 772 Wh.

When measuring the effect of glazing, the existing double-glazed door was replaced with a triple-glazed one. The measurements showed that an additional glass sheet on the door not only increases safety by lowering the temperature of the external glass surface, but also contributes to a higher energy efficiency of the oven. Figure 9 shows the temperature variations in the brick at position 1 (T pt1) and consumed energy (E) at a given air temperature in the oven (T amb) for double (2G) and triple (3G) door glazing. The energy consumption was 837 Wh.

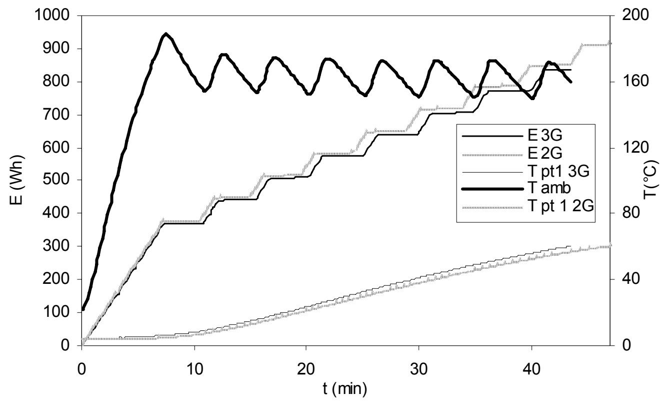

Figure 9 Effect of double (2G) and triple (3G) door glazing.

The influence of insulation layer thickness was analyzed by laying an additional glass wool layer on the sides and on the upper and lower external oven surface. On the rear, no insulation was added because of the vicinity of the electric heaters. A 3 cm layer of glass wool was added – a total of about 1300 g. Figure 10 shows a comparison of the basic oven and the additionally insulated oven (isol). The energy consumption of the oven with additional insulation was 846 Wh.

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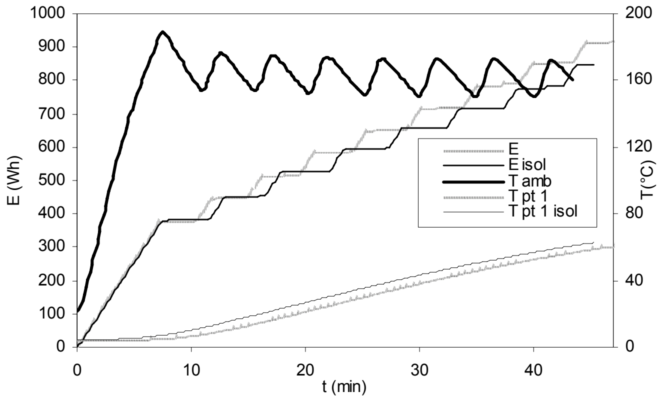


Figure 10 Effect of insulation.

The effect of irradiation inside the oven was tested by placing an aluminum foil onto the oven's inside walls, except for the upper and lower sections, where the heaters are. The foil was arranged in two layers at a distance of about 4 mm. The result for energy consumption is practically the same as the result for measurement with additional thermal insulation, i.e. 845 Wh.

The oven has an integral ON-OFF PID controller. The control regime was analyzed by setting different tolerances for the desired and actual air temperature in the oven. It turned out that small oscillations have a favorable effect on oven energy consumption. Figure 11 shows a comparison of energy consumption (E), temperature variation in the oven (T amb) and temperature in the test brick at measurement site 1 (T pt 1) between the standard control regime and a regime with smaller tolerances between the desired and actual oven temperature (E reg, T amb reg, T pt 1 reg). Energy consumption at improved regulation amounted to 745 Wh.

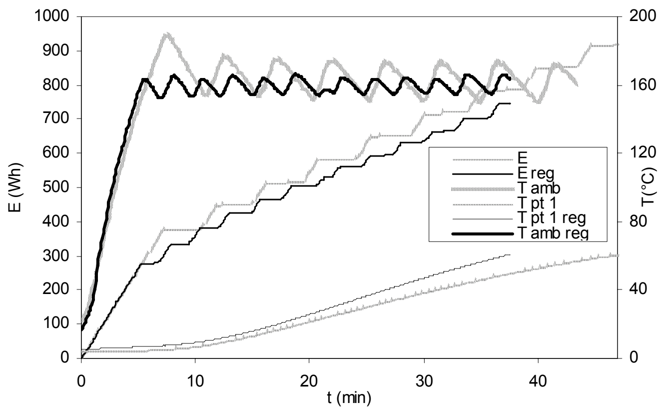
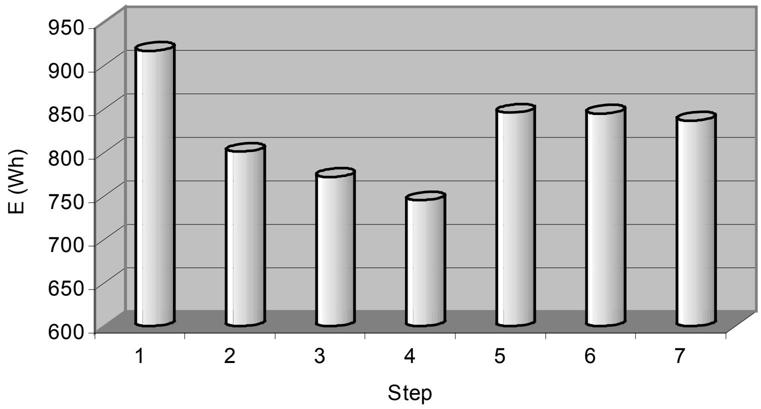


Figure 11 Effect of control.



Step	Description	E (Wh)
1	Standard	917
2	Sealing of the door and gaps	801
3	Sealing of the door, gaps and vapor outlet	772
4	Control with smaller oscillations	745
5	The added 30 mm insulation layer around the oven	846
6	Aluminum foil glued over the interior oven surface	845
7	Triple glazed door	837

Figure 12 Quantitative comparison of measures.

On the basis of analysis of the influence of individual parameters on the energy consumption required for heating the test brick from 5 to 55°C, the above-mentioned measures were quantitatively compared. Figure 12 shows that the control method can contribute at most.

With a balanced combination of individual measures, it was possible to achieve a shift to a higher energy efficiency class for the studied oven. The acquired knowledge may be a good basis for designing ovens with a higher energy efficiency.

Conclusions

On the basis of an analysis of individual influences on the energy efficiency of ovens, several solutions were proposed for improving oven operation. An analytical solution was made for describing the nonstationary temperature field within a test brick with convection at a constant heat transfer coefficient and a continuously variable temperature of the surrounding fluid using Green's functions. The influences of door sealing, vapor outlet slit, additional insulation, the oven regulation regime, door glazing and irradiation within the oven were experimentally analyzed.

On the basis of the proposed improvements, the analyzed mass produced oven was moved to the A class of energy efficiency according to standard EN 50304:2001.

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