Low-order dynamic model of a domestic electric oven
Part I: Experimental characterization of the main heating functions

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Abstract.
Household electric ovens can be considered as one of the most common domestic appliances and they usually represent a low-efficiency category, whose value ranges between 10% and 12%. Usually, oven energy class is determined by means of a test procedure regulated by the EN 60350-1 European standard, which moreover requires a proper control of the oven centre temperature. However, during normal operating conditions, because of the presence of the food at the centre, the temperature control within the cavity occurs on the basis of the temperature measured by a probe usually placed in the proximity of one of the cavity corners. Any analysis aimed at decreasing energy consumption must therefore be able to model in sufficient detail the thermal behaviour of the appliance, while still retaining a degree of simplicity. Lumped parameter models have proved themselves a suitable choice, but, especially for gray-box and black-box types, their parameters need to be estimated and validated through experiments. In this work, a common household oven (Electrolux) was instrumented in order to investigate the temperature distribution within the appliance as a consequence of the operating conditions adopted, with the subsequent aim to model the dynamic behaviour of the oven. The oven was set into a cabinet normally used during the energy consumption test, in order to capture the proper thermal dynamics of the system, and the two main heating functions (forced and natural convection) were also investigated in the range 160-240°C. In addition to the temperature measured by the probe (a Pt500 sensor), several thermocouples were placed within the cavity in order to measure the oven centre temperature and to obtain the mean temperatures of walls and heating elements, while one thermocouple of the same type monitored the temperature of the surrounding environment. The number of thermocouples was chosen by trial and error on the basis of modelling needs. Also, four power meters were used to record the electric power consumption of each heating element and the overall electric power absorbed. Since the ultimate goal of this research activity is to create a dynamic model of the oven for control design purposes, the experimental data obtained in the campaign have subsequently been used for this purpose.

1. Introduction
The increasing awareness of the finiteness of energy sources has spurred scientific research into identifying the main areas of energy consumption and into devising ways to reduce the energy demands at all levels. Among the pre-eminent energy consumers, buildings play a key role, and household appliances contribute almost 25% of the overall demand, [1]. Household ovens belong to this category, and their efficiency, between 10% and 12%, ranks them among the devices with
the largest potential for improvement, [2, 3]. One way to increase the oven performance is to devise control systems and strategies which allow proper control of the oven centre temperature. This is also a compelling requirement for the energy consumption test, which is carried out according to the EN 60350-1 European standard, [4] for electric ovens and determines in which energy category (from A+++ to D) the device will fall. The cheapest way of testing a wide spectrum of control strategies at the feasibility stage is through a mathematical model. The model must be able to replicate in a sufficiently accurate and simple way the dynamic behaviour of the oven in the range of temperatures normally associated with energy consumption tests (160 – 200°C for ventilated operation and 160 – 240°C for static, i.e. non-ventilated, operation [4]). The model is used as a predictive tool for virtual tests and thus spares time-consuming and expensive experiments, but needs to be calibrated with experimental data and validated, again using experimental data as benchmark.

Part I of this paper details the experimental data acquisition procedure and results of tests carried out on a typical household electric oven for different sets of operational conditions. Some of the data were used for parameter estimation in the lumped-parameter model used to characterize the oven, as detailed in Part II [5], and the rest were subsequently employed to validate the model. The choice of a graybox model was mandated by the problem, which is not amenable to the analytical treatment such as for whitebox models, owing in particular to the difficulties in estimating the actual conductance of the oven’s cavity walls. This parameter would be influenced by the actual contact resistance of the rock wool used as insulator, which is hard to estimate, and varies from oven to oven due to manual assembly. It would therefore be difficult to use the data to set up an analytical/semi-analitical model; on the contrary, temperature measurements on the different faces could be employed to estimate the heat flux through each wall and door using an inverse methodology as described in [6, 7].

2. The oven
The oven considered is a commercial model (“Electrolux -EOB6850BOX”) with a 72 dm³ volume of its inner cavity (where food is placed for cooking). The oven is set into a wooden cabinet of the kind usually employed for the energy consumption test. The oven has three heating elements, which can be powered alone or as a combination in the different cooking programmes. The top heater (TH) can supply a maximum heating power of 2300 W, is located in closed proximity to the top wall and is the only one actually inside the cavity. Close to the bottom wall, but on its outer side, is the bottom heater (BH), with a maximum power of 1000 W. The third heater is on the cavity’s rear wall, and is ring-like, as it encircles the outer perimeter of the fan sucking air from the ambient and cavity and conveying it over the ring heater (RH), which has a maximum power of 1900 W, and again to the cavity itself.

Depending on the operational conditions, one or more heaters are active; in particular, the heating modes investigated are reported in Table 1. For each operation mode the active elements are reported in column 1, whilst columns 2 to 4 give the minimum, maximum temperature set-point and temperature interval between two consecutive tests, as prescribed by the European standard, [4].

In order to describe the system in a simple yet effective way, a lumped parameter approach was chosen, as detailed in Part II of this paper. The model entails a number of parameters (equivalent to conductances and capacitances in an electric network) which need to be determined through experiments. In order to do so, several tests were run, and some of the results were employed to determine the model parameters, whilst the remaining data were used for validation purposes. Since the model aims at describing, among others, the time evolution of the temperatures of the air at the oven centre and of the oven temperature transducer (a Pt500 resistance temperature transducer, RTD), a single parameter describing the cavity, as in [8, 9] would not suffice, and a degree of discretisation was needed. Besides the air at the oven centre (OC), it was chosen to
assign representative temperatures to each of the cavity walls: rear (PW), bottom (BW), top (TW), right (RW), left (LW) and glass door (D), and to each heater: TH, BH, RH. The readings of the Pt500 were also needed, as was the ambient air temperature.

Prior to running experiments for the energy consumption tests, the temperature and weight of the wet brick were recorded and checked against the allowable values. During the tests themselves, as prescribed by EN 60350-1, two more temperatures from the thermocouples placed inside the brick were recorded. Under these conditions the temperature at the oven centre could not be measured, so this was estimated from the values of cavity air temperature at four locations 2 cm away from the side walls of the brick.

| Power On         | $T_{\text{min}}$ °C | $T_{\text{max}}$ °C | $\Delta T$ °C |
|------------------|----------------------|----------------------|---------------|
| F+RH             | 160                  | 200                  | 20            |
| TH+BH            | 160                  | 240                  | 40            |
| F+TH             | 160                  | 200                  | 20            |

The power instantly supplied to the heaters was measured independently by means of three LogiLight EM0002$^{\text{TM}}$ power meters, Fig.1, and another device of the same type was employed to meter the total power absorbed. After calibration with a reference power meter (Yokogawa WT210$^{\text{TM}}$) the measurement uncertainty was found to be lower than ±0.5%, whereas the standard for energy consumption requires a maximum uncertainty of ±1%. The power meter were operated through an ad hoc Arduino$^{\text{TM}}$ platform.

![Figure 1: Reference instrument for calibration (left) and power meter assembly (right).](image)

The raw temperature measurements from the built-in Pt500 were recorded through an Advanced Measurement Infrastructure (AMI) device and sent to a LabView application, which also recorded the temperature measurements from the various thermocouples employed, which were collected over a FieldPoint$^{\text{TM}}$ module. All thermocouples were type K and were calibrated in the 1−500°C range. After calibration, the estimated uncertainty of temperature measurements, including the measurement chain, was ±1.0°C, up to the maximum set-point temperature for the test, i.e. 240°C, and a maximum of ±4.5°C in the whole range of temperatures recorded. Total uncertainties have been calculated according to customary practice [10, 11]. The experimental set-up also allowed control laws to be implemented in order to power
the three heaters independently. This option was not used while acquiring data for model calibration and validation purposes. A schematic of the measurement and control loop is shown in Fig. 2.

![Schematic of the measurement and control loop.](image)

One important issue was related to the number of temperature measurement points needed to obtain a representative description of the model components. In fact, the temperature field in the oven cavity and at its boundaries is far from uniform, owing to both the different composition of the walls and the ventilation system.

In particular, the door is composed of several uninsulated, selective glass panes with channels between them through which air drawn from the ambient circulates for cooling purposes, as shown in Fig. 3: two fans, one behind the rear wall, the other above the top wall, draw ambient air in. The air entering from the rear is either blown into the oven cavity from its sides whence it exits from a grid in the rear wall, sucked in by the same, or directed towards the area above the top wall, where the electronic components of the oven are located. The other fan draws air through the channels in the oven door and from vanes at the upper backside of the oven through the electronics and out again. The mother board is a critical component and its temperature must be kept low through the use of high-performance heat sinks such as those described in [12].

A single measurement point would not suffice in some cases, as is illustrated in Fig. 4, which refers to the top wall’s temperature evolution during a transient in the static (i.e. non-ventilated) mode at a set-point of 200°C. Three temperature sets were measured at points along one diagonal of the oven: the top-right corner, \( T_{\text{right}} \), the middle, \( T_{\text{centre}} \), and the bottom-left corner, \( T_{\text{left}} \). The evolution of the temperature obtained from the average of the three recordings, \( T_{\text{mean}} \), is also plotted: it is clear that the latter value is closer to that recorded at the top-right corner than to that of the thermocouple in the middle. During the calibration phase it was also verified that using the value of \( T_{\text{centre}} \) would yield unsatisfactory values for the parameter, which meant poor model performance in the validation tests, whilst good results were obtained when using \( T_{\text{mean}} \). The same situation was encountered for several other locations; for this reason, three measurement points were adopted for each of the cavity’s inner walls, according to the sketch of Fig. 5.

The heating elements were also suitably instrumented with thermocouples fastened at different locations on their surface. Contact between the temperature transducers and the surfaces was ensured by heat resistant tape (Kapton™); in the case of the electric heater, where local temperature could exceed the application range of Kapton™, the thermocouples were also held
Figure 3: Airflow in the oven.

Figure 4: Temperature plots for three locations on the top wall and mean temperature. Static mode at 200°C

Figure 5: Layout of the thermocouples on the cavity walls (left) and pictures of the thermocouples in place (right).

in place by steel wires. Figure 6 shows the temperature evolution of three thermocouples on the TH during a test with the fan powered off (static mode) at a set-point of 200°C: the excellent agreement of the two thermocouples which are symmetric to the heater’s supply’s contacts is ±3.7°C, within the uncertainty bonds for a measured temperature of 413°C.

When running energy consumption tests, a brick prepared according to the prescription of EN 60350-1 was laid onto a tray inside the cavity. The standard also requires that its temperature be determined by measurement at two points inside the brick [4].

In order to obtain a satisfactory description of the brick in the lumped-parameter model, a temperature representative of the brick surface was needed. One thermocouple was therefore embedded at surface level into each of the brick’s faces, as shown left in Fig. 7. Also, in order to
obtain a suitable piece of information to compute the temperature of the air at the oven centre, four thermocouples were placed perpendicular to the grid onto which the brick is laid during the EC test about 2 cm from its side, see Fig. 7 right.

2.1. Overall uncertainty

The overall uncertainty is calculated straightforwardly, without any involved sensitivity coefficients as for other cases, [13], since nearly all the quantities of interest to estimate the parameters of the graybox model of the oven presented in part II of this paper, [5], are either measured directly (e.g. the power supplied to the heaters) or are an average of measurements at different locations, such as the temperatures representative of the cavity’s faces (in this case the value used is the mean of the measured temperatures at three locations). To adopt a conservative approach it can therefore be assumed that the uncertainties of the derived quantities coincide with those of the measured quantities. In the example above, the uncertainty on the surface temperature of one face is the same as that of the single temperature measurement, i.e. ±1.0°C, when application of the procedure described in [11] would yield a value of ±1.0/√3°C.
3. Results

Several tests were run to collect data for parameter estimation of the model and its validation, under the experimental conditions listed in Table 1. Some of the tests were aimed at determining the most satisfactory layout of the temperature sensors to yield results which could be meaningfully employed in the model, an example of which has already been shown in Fig.4. Some results are reported in the following to highlight peculiarities of the process.

Figure 8 shows both the power up and temperature history of the top heater during a static (i.e. without ventilation) test at 200°C. It is clear how the temperature follows the power up cycles, but it can also be noticed that, when the heater is in operation, the power supply is not uniform, and decreases, if slowly, in time. This is due to both fluctuations in the network supply and changes in the value of the heater’s resistance, which depends on temperature.

Figure 9 shows the temperature versus time during a stationary test at 200°C of set-point for the oven centre, of the Pt500 as obtained through the AMI, and that of a thermocouple fastened onto the surface of the RTD, as detailed in the picture. Both the ramp during the transient phase and the wobbling behaviour once steady state conditions are reached can be easily discerned. It is also interesting to notice that the OC temperature shows no overshoot, whilst both the Pt500 and the thermocouple do: this is due to the lack of ventilation and to the location of the Pt500, close to the top heater, which is used in this mode. As a consequence, the Pt500 heats up faster than the oven air, and the thermocouple even more so. It can also be noticed that the Pt500 lags slightly behind the thermocouple, which is exposed more directly to the heater and, above all, has a smaller thermal inertia. It would seem puzzling that the readings of the Pt500 show a temperature that oscillates around the set-point and consistent with that of the oven centre once the transient is over, whereas the recordings of the thermocouple onto the RTD sensor are higher. In fact, the Pt500 readings are automatically corrected by the manufacturer to account for the shift between actual temperature at the location of the RTD and that at the oven centre. The AMI device reads the compensated signal, which is consistent with the set-point.

The temperature evolution for one ventilated (top) and one static (bottom) test at 200°C set-point is shown in Fig.10. Whilst temperatures at the outer surface and in the channel between the glass panes are only slightly different, the effect of forced convection can be appreciated at the inner surface of the door, where the temperature is almost thirty degrees cooler than for the
static case. This also explains why manufacturers carry out the energy consumption test with
the fan on.

Figure 10: Temperature across the oven door in the ventilated (top) and static (bottom) cases, for an operational set-point of 200°C.

The temperature at the six locations on the brick surface is shown in Fig. 11 for a set-point of 200°C. In both cases the lowest temperatures are associated with the bottom surface; this is because the brick has been left to soak at least eight hours as per the requirements of the EC test, and the cold water seeps through the porous structure and drips from the bottom. The highest temperature during ventilation is that associated with the brick’s rear: this is because in this heating mode the fan, which faces the rear of the brick, is powered and draws air from the cavity, thus accelerating surface evaporation and decreasing the local thermal capacity. Also, in the ventilated mode temperatures at the different locations, with the exception of the rear, are much closer to one another and higher than in the static case. The forced flow of air, which enters from the sides of the cavity and exits through the fan, acts so as to make conditions more homogeneous and to increase heat transfer from the cold brick to the hotter cavity air.
4. Conclusions
In this work the experimental set-up of a domestic oven has been described. Temperature and power measured at suitable locations are used to estimate the parameters of a lumped model which aims at describing the dynamic behaviour of the oven both empty and in the conditions of the energy consumption test. The data collected and not employed in the estimation procedure have been used to validate the model, with results illustrated in Part II of this paper in the case of non-ventilated operation with an empty oven.
Other forms of the model, for ventilated operation with an empty oven and for the EC test have also been validated with the data collected in the experimental campaign, and these results will be published at a later stage.
Acknowledgements
The Authors wish to acknowledge Electrolux Italia S.p.a. for supplying the test oven and for funding this research.

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