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Energy Efficiency of Combined Ovens

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Abstract

The management optimization of energy fluxes applied in the professional cooking sector has an attractive potential, and represents a big step ahead, because it is characterized by a high energy demand and has a large diffusion all over the world. Furthermore, professional cooking sector still presents significant possibilities for energy efficiency enhancements, in both design solutions and operating strategies. The present study focuses on energy efficiency analyses on combined ovens for professional use. In the initial phase of the evaluation, energy efficiency standards EFCEM, ENAC and ASTM have been compared with experimental results. Discrepancies were shown by means of a systemic application of the mentioned standards to a specially instrumented prototype of professional oven. Different test conditions do not allow a meaningful comparison of test results, leading to the definition of a new methodology for the energy efficiency evaluation of a combined oven. structured on the experimental analysis of the balance of fluxes incoming and outcoming from the oven in different cooking modalities. It allows improving the knowledge of the machine and, afterwards, helps in the definition of different design choices, derived from the analysis.

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Keywords: combined oven;energy certification;oven energy balance.

1. Introduction

The challenging worldwide energy demand requires the economical and technical development of alternative energy sources and a restriction of the energy consumption by means of systems and machines that are more efficient. This permits an optimal management of energy fluxes. Food-service facilities, having an average energy use almost three times higher than other commercial activities, can be considered as an energy intensive field and, consequently, a sector with significant potentials for energy efficiency improvements. Moreover, eighty percent of the annual energy bill expenditures for commercial food services are wasted due to the use of inefficient equipments[1].

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Nomenclature

A	radius of
B	position of
c_k	specific heat, *k* stands for individual food component (i), load ($load$) or tray ($tray$) [W/m^2 °C]
E_k	energy, *k* stands for energy lost through the opening of the door (*door*), steam exiting (*vent*), wall ($wall$), drain of liquids (liq) or for energy adsorbed by the Gastronorm trays and lids (*GN*) (Lid), auxiliary (aux) or energy introduced from the water entering (w), electricity (*el*) or energy adsorbed by the load ($load$) [kJ]
h	specific enthalpy [kJ/kg]
m_k	mass, *k* stands for trays, water inlet, loss or gain in the load, liquid discharge and condensed [kg]
m_{load}	mass at the end of the cooking process [kg]
$\dot{m}$	mass flow [Kg/s]
m_{cv}	mass inside the control volume [Kg]
Q_{cv}	net amount of heat supplied to the control volume [kJ]
ΔT_{tray}	temperature difference reached by trays [°C]
ΔT_{load}	temperature difference reached by the load [°C]
U_{cv}	internal energy [kJ]
x_i	mass fraction of the food component *i* [kg/kg]
W_{cv}	net amount of energy transferred as work [kJ]
η_i	efficiency [%]
λ	latent heat of evaporation [kJ/kg]

Energy performances of consumer and professional appliances are receiving more attention in the product development. For example, the European Community SAVE programme has promoted the efficient use of energy, in particular in domestic appliances [2].This paper focuses on professional ovens, which consume a large amount of energy. They need to satisfy high quality standards, high adaptability and reliability but they still do not have worldwide recognized standards for energy classification. The first purpose of this study is to analyse three test procedures for cooking appliances: EFCEM, ENAK and ASTM. They differ in the test methodology, load types, load conditions and on the definition of energy efficiency parameters. The analysis has highlighted an impossible comparison among the results and a consequent difficult evaluation of the energy efficiency of the oven. The subsequent step of the work presented in this paper is the identification and the development of a detailed methodology for analysing the energy efficiency of the oven. The result of the methodology is then a guide in the identification of improved design technical solutions. Some of these are finally applied, showing remarkable results in the overall energy efficiency of the oven.

2. Test comparison

Test procedures define a structured methodology for the evaluation of energy performances of professional combined ovens. They consider measurements, in different cooking modalities, of water consumption, energy consumption and variation of weight of the loads that are inside the cavity. An analysis of the parameters of interest is presented in [3]. For a better understanding of the thermodynamic behavior of the oven, a comparison among the following energy test procedures has been carried on:

- EFCEM [4]: it evaluates energy consumption in two cooking modalities: convection and steam. The thermal loads are fifteen water-saturated bricks in convective test and water-filled trays without lid in steam test;
- EFCEM [5]: it evaluates the energy efficiency for combined cooking mode. The thermal loads are water-filled trays with lids having a hole in the center;
- ENAK/SVGG [6]: it evaluates the energy consumption. The thermal loads are either water-saturated bricks or water-filled trays;
- ASTM F2861-10 [7]: it evaluates the energy efficiency. The thermal loads are potatoes.

A combined electric oven Electrolux AoS Touchline, type 10 GN 1/1 LW level, was used for the tests. It has a declared power of 17 kW in convection and steam mode (400 A), the internal cavity has a volume of $0.35m^3$.The comparison was made on the energy efficiency yield, which is defined for an oven as the ratio between the heat given to the thermal load and the energy introduced in the system. The heat given to the thermal load can consider the presence of trays and lids or not. The following formulations are different definitions of energy efficiency yields:

$$\eta_1=\frac{(m_{load}\cdot c_{load}\cdot \Delta T_{load})}{E_{el}+E_{GN}+E_{Lid}}=\eta_{EFCEM,combi} \tag{1}$$

$$\eta_2=\frac{(m_{load}\cdot c_{load}\cdot \Delta T_{load})}{E_{el}} \tag{2}$$

$$\eta_3=\frac{\left[(m_{load}\cdot c_{load}\cdot \Delta T_{load})+\left(m_{tray}\cdot c_{tray}\cdot \Delta T_{tray}\right)\right]}{E_{el}}=\eta_{ASTM,steam} \tag{3}$$

$$\eta_4=\frac{\left[(m_{load}\cdot c_{load}\cdot \Delta T)+\left(m_{tray}\cdot c_{tray}\cdot \Delta T_{tray}\right)+(\lambda\cdot \Delta m_{load})\right]}{E_{el}}=\eta_{ASTM,conv} \tag{4}$$

The results of the analysis on the test procedures are reported in Tab 1 [3], where the values of energy yields in respect to the different test methodologies are reported. The energy efficiency yields calculation in the combined cooking mode is not considered in ASTM conditions, that take into account only the temperature variability from one pot to another (cooking uniformity), using ice as load. Parameter $\eta_4$was not calculated for the steam cooking mode, because weight losses due to the evaporation of the loads are hidden by the increased weight from the condensation of the steam, used as heating vector. Comparing the columns of Tab 1, it is possible to analyse the different definitions of energy efficiency yields. Instead, making a comparison between the rows of Tab 1, it is possible to analyse the different sets for each standard procedure. The small differences betweenη_1 andη_2, calculated for the same test, show that the influence of weights and trapped energy of trays and lids is negligible. The values calculated forη_1 andη_3 show small differences and highlight that the different methods for considering the energy adsorbed by the trays do not significantly influence the results. Comparing η_3 andη_4 ,it is possible to examine the impact of the latent heat of evaporation.

Table 1. Energy yield

Cooking Mode	Test Method	η_1	η_2	η_3	η_4
Conv.	EFCEM	41.0	41.0	44.3	83.4
	ENAK	24.7	24.7	25.6	68.2
	ASTM	32.4	32.5	33.9	88.5
Steam	EFCEM	68.3	68.2	72.9	/
	ENAK bricks	21.4	21.4	22.5	/
	ENAK water	64.5	64.7	68.8	/
	ASTM	38.3	38.2	41.0	/
Combi	EFCEM	59.5	59.8	65.8	69.9
	ENAK	44.2	44.2	47.5	89.6
	ASTM	/	/	/	/

3. Energy characterization of the oven

The energy fraction absorbed by the food during cooking is low because a large portion of energy goes into the structure of the oven (e.g. walls, door and insulation), and is lost in the surrounding environment [8]. High-emissivity linings absorb the thermal radiation energy from the cavity and then it is lost through conductive bridges and convective leaks [9]. Furthermore, a lot of energy is lost through the venting of the evaporated moisture from the cavity. The analysis of the data from the test procedures show the need of a more comprehensive testing methodology for defining and calculating the balances of energy, which are required for a better characterization of the thermodynamic behaviour of the oven and to have an easier procedure for guiding the design phase. For calculating energy balances, the versions “6” of the draft EFCEM was integrated with a series of measurements needed for characterizing the energy fluxes not considered in the test procedures. The aim of the measurements is the determination of the enthalpy and energy content of the fluxes which enter and leave the oven considered as a control volume [10-11].Considering the schema of an oven as in Fig.1, it is possible to identify the power supplied (electricity or gas) and the fluxes of air inlet, water inlet, water discharge and exhaust fumes.

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For calculating the balances of mass and energy two cooking modalities are considered [12]:

- Convection: in the center of the cavity a temperature of 160 °C is set and 15 water saturated bricks are used for the tests.
- Steam: in the center of the cavity a temperature of 100 °C and a relative humidity of 100% are set. Ten water trays with a welded top are used for the load. The welded top has a hole at the centre.

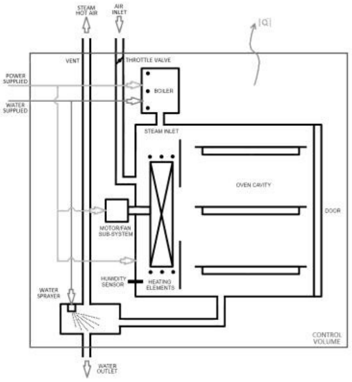

Fig.1. Oven schema

Basically the oven during the cooking process changes its thermodynamic state. It is not possible to consider steady state conditions, because parameters as work, energy and mass fluxes continuatively change during the test [13].

Generally speaking, the mass balance applied to a control volume during a transient period is given by Eq. 5, where the subscript *i* indicates the inflows, *e* the outflows, and the subscript *cv* the control volume.

$$\Delta m_{CV}=\int_0^t\left(\frac{dm_{cv}}{dt}\right)dt=m_{CV}(t)-m_{CV}(0)=\int_0^t\left(\sum_i \dot{m}_i\right)dt-\int_0^t\left(\sum_e \dot{m}_e\right)dt=\sum_i m_i-\sum_e m_e \tag{5}$$

The mass balance can be written in a more compact formas in Eq. 6 with reference to the convective modality test, and as in Eq.7 when steam modality is taken into account.

$$\Delta m_{CV}=\left|m_{Water\_Inlet}+m_{Load\_Weight\_Loss}-m_{Condensed\_Vent}-m_{Liquid\_Discharge}\right| \tag{6}$$

$$\Delta m_{CV}=\left|m_{Water\_Inlet}-m_{Liquid\_Discharge}-m_{Condensed\_Vent}-m_{Load\_Weight\_Gained}\right| \tag{7}$$

If the variations of potential and kinetic energy between inputs and outputs are negligible, the balance of energy fluxes is represented in integral form as in Eq.8:

$$\Delta U_{CV}=U_{cv}(t)-U_{cv}(0)=Q_{cv}-W_{cv}+\sum_i\left(\int_0^t \dot{m}_i\, h_i dt\right)-\sum_e\left(\int_0^t \dot{m}_e\, h_e dt\right) \tag{8}$$

If the initial and final test conditions are the same, the internal energy of the system does not change, and Eq.8can be further simplified as:

$$Q_{cv}-W_{cv}=\sum_e\left(\int_0^t \dot{m}_e\, h_e dt\right)-\sum_i\left(\int_0^t \dot{m}_i\, h_i dt\right) \tag{9}$$

With reference to the oven schema reported in Fig.1, Eq. 9 can be written as follows:

$$E_{vent}=E_{el}-E_{aux}-E_{load}-E_{liq}-E_{wall}-E_{door}+E_w \tag{10}$$

In Eq. 10 the energy adsorbed by the load in the cavity at the end of the cooking process,E_{load} , is given by Eq.11, where the specific heat of the load is determined with a weighted average as $c_{load}=\sum c_i x_i$.

$$E_{load}=(m_{load}\cdot c_{load}\cdot\Delta T_{load})+(m_{tray}\cdot c_{tray}\cdot\Delta T_{tray}) \tag{11}$$

As example are reported the pie charts representing the percentage distribution of the energy fluxes in convection Fig.2.(a), and steam Fig.2.(b)mode.

Energy absorbed by the load is measured with Eq.11 weighing the mass after the cooking process and measuring the temperature in the centre of the load before and after the cooking process. In this measurement is considered also the energy given to the trays. Energy dissipation due to the opening of the door is also measured. During one hour test, three door openings, which last in three minutes, are made every twenty minutes. The resulting energy loss through the door is calculated by the difference between the power consumption in one hour when the door is opened and closed and the power consumption of maintenance. The last one is the energy rate dissipated through the walls, and is calculated with a measurement of the power consumption at a certain temperature on an un-loaded oven, in convective cooking mode. Energy introduced and dissipated by the liquids is calculated on the bases of temperatures and flow rates data and integrated by means of a proprietary program [14]. Energy loss through vapours is calculated by means of Eq.10.

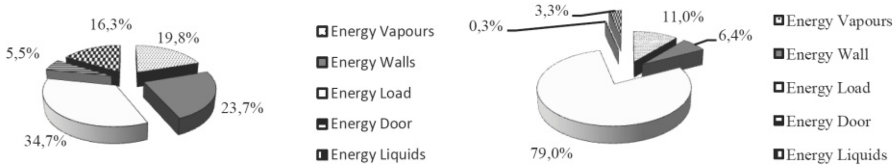

Fig.2.(a) Energy fluxes in convection mode; (b) Energy fluxes in steam mode.

4. Technical solutions

The proposed methodology has highlighted some technical solutions, capable to guarantee significant energy savings, an overall acceptance by the customers and also a quite cheap industrialization. They are listed in Tab.2, which is organized as the ones reported in [2], with reference to domestic ovens, to allow a comparison with the professional appliances here considered.

Table 2.Technical solutions

	Design Option	Energy saving	Consumer Response	Test in prototype
1	Improve thermal insulation (a, b)	0-11	Acceptable	Yes
2	Improve cavity thermal insulation	7-8	Acceptable	Yes
3	Reduce mass of oven structure	10-18	Acceptable	Yes
4	Unglazed door	7-25	Unacceptable	No
5	Optimized glazed door design	4-12	Acceptable	No
6	Passive cooling for glazed door	0-8	Acceptable	No
7	Optimised vent flow	8 or 12	Acceptable	No
8	Aluminium foil on cavity walls	7-10	Acceptable	No
9	Reduce cavity volume	0-4	Acceptable	Yes
10	Reduce cavity opening access	0-4	Acceptable	No
11	Control with smaller oscillations	15	Acceptable	Yes
12	Reduce auxiliary energy	1-4	Acceptable	No

Table 3. Results of the Analysis

	One 10-1/1	Prototype 10 1/1	%Difference
Energy for maintenance [KJ]	5595	3960	-29.2
Energy given to the structure [KJ]	3924	3285	-16.3
Cavity Volume [m^3]	0.35	0.316	-9.7

For each design option, the potential energy savings are represented in column 3.The fourth column represents the customer response to a new implemented solution, because an oven can be efficient but, if it is perceived as dangerous or the cooking performances are not good as before, the implemented new technical solution would be unacceptable for the customer. In this analysis, the interactions between design options have not been taken into account, even if it is known that energy saving is not a linear process. This means that the result of combined technical solutions could not simply be the sum of the effects of every single improvement. Some of such technical solutions have been until now applied to a prototype, as indicated in the last column of Tab. 2.In Tab.3 the results of the analysis applied to the oven prototype are represented and compared with the corresponding data of the actual oven One generation 10-1/1. The comparison is made with reference to the power consumption for the maintenance, the energy given to the structure and the cavity volume.

The values are calculated from plot of measurements as the one represented in Fig.3.In abscissa is represented the time of measurements and in ordinate are reported the measured temperatures.

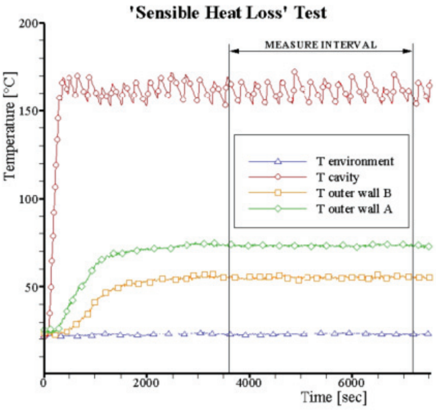

Fig.3. Plot of measurements

They are detected in the centre of the cavity and on its outer walls, in the locations where temperatures resulted to be higher. The temperature behaviour permits to study the energetic performances of the oven, characterised by different phases [15]. The energy consumed in the first hour represents the oven performances in the transition phase. After a transition phase, the oven reaches the operating conditions. The second hour of Fig.3identifies the energy needed for maintain the operating conditions. The difference between the energy consumed in the first hour and the energy consumed in the second hour represents the energy absorbed by the structure. The cavity volume is an important factor affecting the energy performances. Small cavity volumes have less dispersion of energy and permit higher energy efficiency. A comparison between the results of the analyses on the oven One Generation 10 1/1 and the prototype is presented in the fourth column of table 3.The results are remarkable because there is a 29.2% lower required energy for maintenance of the operating conditions in the prototype and a 16.3% lower energy given to the structure. The cavity volume in the prototype is 9.7% lower.

5. Conclusions

The methodological approach presented in this article is divided in three phases. In the first phase three different test procedures EFCEM, ENAK and ASTM were compared. These test procedures show differences in the settings and in the definition of the energy efficiency yields. In the second phase a methodology based on balance of fluxes entering and going out from the oven control volume is developed considering different cooking modes as the convection mode and steam mode. This methodology permits a fundamental understanding of the thermodynamic behaviour of the oven in respect to the results coming out from the application of the general procedures and standards. With the developed methodology is possible to establish an energy efficient design and to identify possible technical solutions for reach an efficient energy implementation. In the third phase some technical solutions were applied to an oven prototype and then analysed experimentally showing 29.2 % of energy savings.

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Biography

Burlon holds a bachelor's degree and master's degree in Engineering. Burlon is currently a PhD student in Engineering in the University of Triest. His PhD is funded by Electrolux Professional. Burlon's research interests revolve around energy efficiencies studies and computational modelling of Professional Appliances.