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GEOMETRIC DESIGN FOR THERMAL AND DEFORMATION PERFORMANCE OF INDUSTRIAL WAFER BAKING PLATES

Márcio César Carzino
Marcelo Risso Errera
Graduate Program in Environmental Engineering, PPGEA, Federal University of Paraná, Av. Cel. Francisco H. dos Santos, 100 - Jardim das Américas, Curitiba - PR, 81530-000
marcio.cesar.carzino@gmail.com
errera@ufpr.br

George Stanescu
Department of Mechanical Engineering, Federal University of Paraná, Av. Cel. Francisco H. dos Santos, 100 - Jardim das Américas, Curitiba - PR, 81530-000
stanescu@ufpr.br

Abstract. *Wafer baking ovens are widely used in the world. They are produced in large scale and are under continuous development, particularly with the goal to reduce waste and energy consumption by all stakeholders while meeting the demand to increase productivity and product final quality. This paper addresses the thermal design of the baking plates of wafer gas ovens under operating and deformation constraints. We consider the effect of gas flames thermal interaction with the baking plates. The gas burners flames are simulated as a set of radiant solid strips with fixed geometry and imposed heat flux. The thermal radiation is the heat transfer mechanism prevailing from burners to the finned back of the baking plates from which steady state, three-dimensional, heat conduction takes place to the baking surface at the opposite side. A commercial finite-element software is used for computing the mathematical modeling and the physics interactions. Different designs for plates are evaluate by the Constructal Design method in order to seek better thermal solution for baking surface of the plates. The possibility of different geometric fins is considered for finite and fixed volume and assessed in this new study. We tested rectangular, trapezoidal, parabolic, triangular, pyramidal, cuneiform fins and with different numbers as well. Initial results showed the baking plate with large numbers long fins provides a better heat transfer and more uniform heat distribution on the baking surface when compared to the three-long-fins plate. The overall gain is approximately 10%. In general, a better heat transfer bakes the product with better coloring and uniform humidity, which in turn provides a good final quality of the product. The mechanical resistance is also evaluated, resulting around less 17% material a providing the same strength*

Keywords: *baking plate, wafer oven, constructal design**,** radiation heat transfer, heat conduction*

1. INTRODUCTION

Wafers are essentially cookies which are baked under pressure between plates. They go centuries back when monks used two cast iron molds to bake them (Moor, 1994). From simple home-style baking plates to today's complex automated ovens, the industry evolved in order to meet the demand for large production and quality standards. The baking process, the quality, productivity, and automation are the main work fronts for improvements including ultimately reduction of wastes and energy. In view of the large-scale production, even incremental gains lead to substantial benefits year-round since today's world production is about 2.85 Mt/yr. In the interior of baking ovens there is a set of lower and upper baking tongs that are assembled on a trolley chain (Fig. 1). The baking trolley moves through the oven in a loop over rails fixed in the structure (Haas et al., 1984). Heat is transferred to the baking trolley through the nozzle burners mounted in pipes located under the carts (for combustion requirements the distance is approximately 50 mm). The burners are located along the longitudinal direction of the oven, and the baking trolley moves along the oven with the plate fins receiving heat from burners (Carzino et al., 2019). The oven operates under specified settings for temperature (baking) and the heat distribution on the plates plays an important role during the baking. Non-uniformity either generates hotter spots (over baked or burned) or colder spots where it concentrates moisture. The latter becomes a quality nonconformity for the key attribute of wafer, namely, crunchiness.

The literature is very limited on industrial baking plates, perhaps for being proprietary knowhow, and thus no similar study was found in the main scientific database (Carzino et al., 2019).

The heat transfer mechanism from the burners to the plates is essentially radiative. We model the heat source as slender rectangle radiating solid strips at high temperature in order to simulate the porous medium burner emitting radiation. The design that is under study is the thermal radiation from the burners and the heat flow to the baking side of the plates. Steady state, three-dimensional simulation of heat conduction through the baking plate determines the superficial temperature of the opposite side where baking takes place. All the physics is modelled mathematically and solved in commercial finite-element software (COMSOL, 2019)

The design of baking plates for the adequate temperature level, with low temperature non-uniformity, sturdiness to stay flat while the lightest possible in order to demand less energy to be moved along the oven and for baking is a challenge that requires an integrated method such as Constructal Design (Bejan and Lorente, 2008). According to the method, the better designs promote greater access of the heat flow across the fins ultimately improving the heating of the baking plate and more uniform stress flow. Earlier, the method of Constructal Design has been successfully employed in the study of extended surfaces under pure convective regimes (e.g., Bejan and Almogbel, 2000).

The thermal performance of different designs (configurations) is observed based on the temperature level and the temperature distribution on the baking surface: the greater the heat access, the higher the temperature, and the lower the non-uniformity on the baking side of the plate.

In this paper we explored different possibilities and number of the extended surfaces shapes, namely, triangular, rectangular, trapezoidal, pyramidal and cuneiform. Initial tests were done from 3 to 17 fins in a total of 119 different computer simulations. So purpose of this paper is to analyze the influence of the shape and the numbers of the fins on the heat transfer from the burners to the back of the baking plates and how heat conduction occurs inside the plates and how homogeneous the temperature on the cooking surface is. It was possible to determine the envelope of feasible designs and the respective performances, which in turn, will provide a landscape for enhancement of baking plates for either yield more thermal performance with the same amount of material, or less material for the same thermal performance. Results showed that is possible to reach 10% thermal gain between two distinct designs while holding same level of deformation and how the performance is affected by external factors (cost, manufacture, operation, etc.).

2. WAFER BAKING OVENS WORKING DESCRIPTION

Baking ovens are well known and largely produced in the world. They allow the food industry to produce several kinds of different biscuits, namely, flat wafers, hollow wafer, waffles, pancakes, bricelets, rolls, ice cream cones among many others. The automatic ovens for wafer baking in general have a cooking cycle that begins with the opening of the pair of baking plates (Fig. 2) in the frontal cabinet of the machine. When the plates are completely open, an injector device deposits the liquid batter directly on the bottom plate. Then the upper plate closes precisely on the lower plate, and a device closes the baking tongs and seals the plate so thats the cooking process is under pressure. A set of baking trolleys forms a chain. The burners transfer heat to the bottom plate, and when the trolleys reaches the end of the oven, the baking carts turns 180° and go back through the set of lower rails, receiving heat in the upper plate until the moment they return to the cabin again and the tongs open and the wafer sheet can be removed (Fig. 1). The process is considered a quick bake, with a duration of the cycle of about 2 minutes (Haas, et al. 1984).

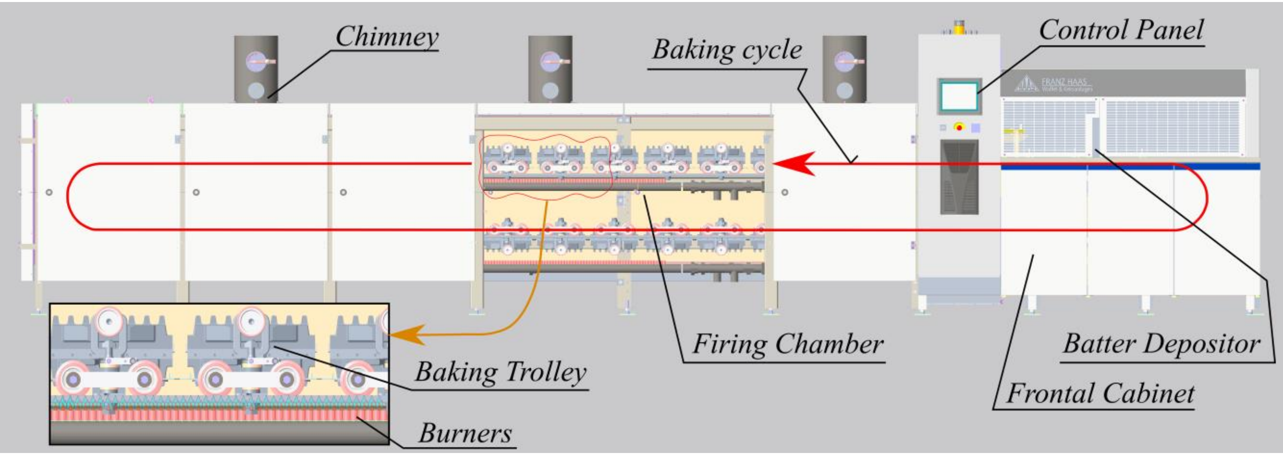

Figure 1. Schematic drawing of an industrial flat wafer oven and its parts. (Source: The Autor)

Gas burners (NG or LPG) provide the heat by the exposed flames. The baking plates move across to the burner nozzles. The heat is absorbed by the fins on the back of the cooking plate and it flows by conduction through the cast iron plates to reach the baking surface, where the wafer batter is baked at a temperature of approximately 160 °C and 180 °C, which in turn depends of the wafer recipe and ingredients (Tiefenbacher, 2014).

3. PHYSICAL AND MATHEMATICAL MODEL

The bottom side of a single plate is considered in order to receive the heating process from the burners by the extended surfaces called fins (Fig. 2). The flames are considered to form a continuous flat plate that produces a heat flux of 80 kWm^{-2} by radiation mainly, considering five burner lanes that distributes the heating through the plate, the heat transfer by thermal radiation prevails. At the industrial process for baking the infrared sensor read the temperature of the baking plate and send the reading to programmable logic controller that determines the level of the heating by a PID setting. Like the thermal mass of the baking plate of cast iron is large was considered a fixed temperature for all process. Even though the baking process is transient, the process is considered steady-state at average conditions (cooking heat and temperature) because over time conditions do not change. The firing chamber temperature is assumed to be 150 °C, considering the combustion gases removed by forced exhaustion. The view factor between the virtual flame and the finned surface is calculated for each point along the surface coupled with the finite element method. Surfaces are opaque. The heat balance will be described later. The mathematical modelling is a bi-dimensional solution. For the first step of the design process, the heat flux demanded by the baking process is due a highly convective regime at the batter side, namely, 100 $Wm^{-2}K$ this value is applied for convective heat flux in biscuit ovens (Sakin *et al.*, 2009).

For sake of brevity, readers are directed to classic heat transfer textbooks (e.g. Incropera, 2003 and Bejan, 1993) for the details of the thermal radiation model for every point lying along the finned surface (Fig. 2). The surface temperature field is coupled with 2-D, steady-state conduction with homogenous and isotropic thermal conductivity in the plate as Eq. (1).

$$\frac{\partial^2 T_p}{\partial x^2} + \frac{\partial^2 T_p}{\partial y^2} = 0 \tag{1}$$

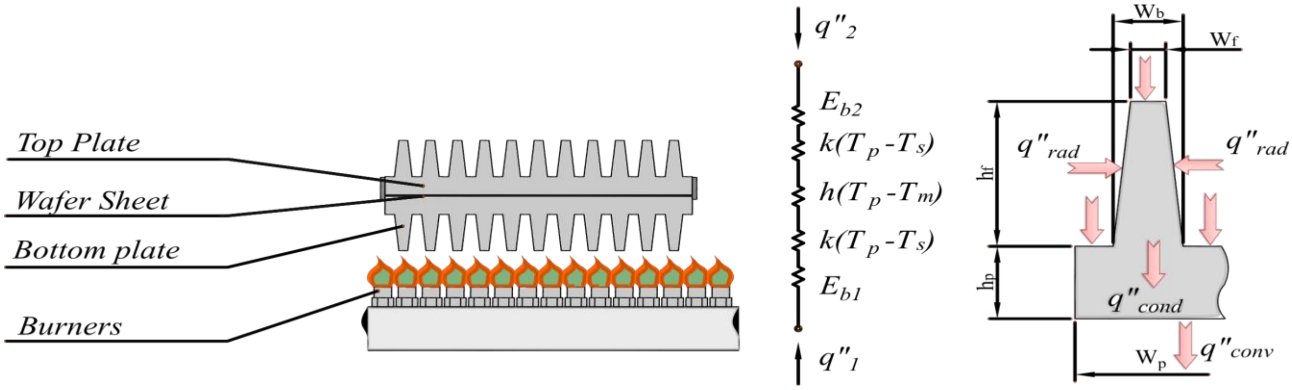

Figure 2. Schematic drawing of a baking plate with burners with heat transfer circuit and a slice of the baking plate and main dimensions. (Source: The Autor)

The temperature of the plate $T_p(x,y)$ lies in a domain with x ranging from 0 to W_p, where W_p is the width of the base of the plate, and y ranging from 0 to h_t, where h_t is the total height of the baking plate, $h_p + h_t$, the height of the base baking plate plus the height of the fins.

The numerical solutions in the commercial software COMSOL were tested by the usual procedures of meshing and validity. This procedure is omitted of the sake of conciseness as well.

The design of the baking plate must be within some constructive dimensions necessary for project and some degrees of freedom were defined by Constructal Design. The material used for baking plates is nodular cast iron (3,7C-3Si). The heating was designed like a flat flame along the baking plates irradiating to the fins of the back of baking plates, the flames are from propane gas at a high temperature irradiating.

The internal ambient temperature of the firing chamber is considered constant and uniform as 150 ºC. The batter is deposited at the initial temperature of 20 ºC (Tiefenbacher, 2014). The mean temperature of the flame is considered to be 1,400 ºC.

The properties of the baking plate are, the heat capacity of C_{pff} = 460,55 $J.kg^{-1}.K^{-1}$, the mass density of 7,200 $kg.m^{-3}$, thermal conductivity of 52 $W.m^{-1}.K^{-1}$ and the surface emissivity of 0.67 (Bejan, 1993).

An oven yields around 12 kW per baking plate, this means 68.000 W/m^2 installed but part of it is lost. It was then considered a heat transfer flux of 20.000 W/m^2 for each plate by radiation surface-to-surface, with controlled opacity.

The overall emissivity of the flame was set as 0.23 considering mainly CO_2 e O_2 as combustion products (Andersson and Johnsson, 2016)

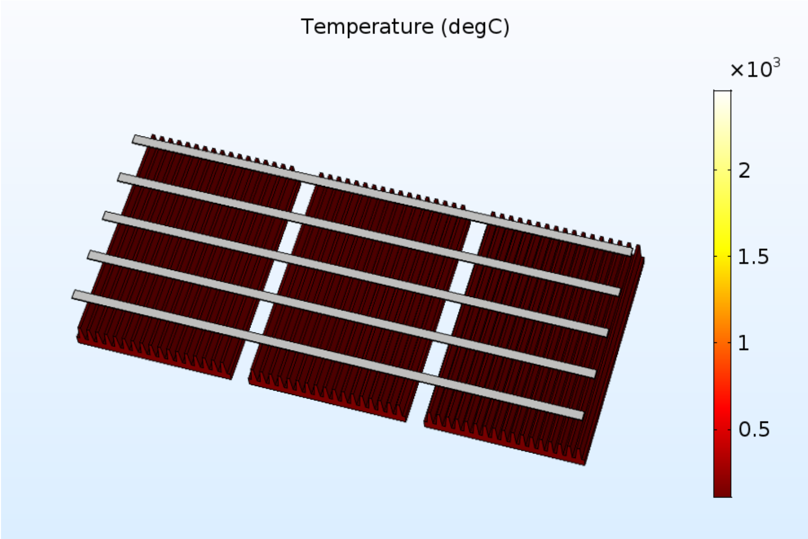

Figure 3. Temperature field of the middle plate with 17 trapezoidal fins and the flat radiant burner. (Source: The Autor)

The software computes the total radiosity, that is, the rate at which radiation leaves the flame due to emission and reflection in all directions per unit baking plate area including de extended areas from fins. The flame condition was simplified as a solid body emitting radiation with a constant emissivity during an average baking time. Irradiation of the flame is diffuse, as well as the baking plates surfaces. The radiation spectrum solely depends on the temperature of the baking plates (Eck *et al.*, 2016).

In short, the mathematical formulation consists of computing the heating emitted by the burners, the heating transferred to baking plates and the heat transferred from baking plates to wafer biscuit undergoing baking. The physics calculation is considered bi-dimensional (2-D). The remaining hypothesis are stated below:

1. steady-state operation of the baking plates running by the oven, because of great mass of cast iron from the baking plates;
2. heat losses for surroundings are negligible because of thermal insulation of the oven;
3. diffuse radiation is the predominant mechanism of heat transfer inside the oven;
4. all flows throughout the oven are considered constant pressure flows;
5. the liquid batter deposited on baking plate is scaled by the boiling water heating transfer coefficient;
6. the ambient temperature of the oven is considered stable around 150 ºC, by the medium temperature of the literature (Mukherjee *et al.*, 2017).

Energy balance considers the heat transfer modes by conduction, convection and radiation in each surface. The energy balance at the rear surface of the baking plate is given by:

$$\dot{q}_{cond} + \dot{q}_{conv} + \dot{q}_{rad} = 0 \quad (2)$$

Where q_{rad} [W] is the energy transmitted by the burner by radiation, and it can be defined accounted for as follows:

$$\dot{q}_{rad} = A_s \ F_{bp} \left(J_b - J_p\right) \quad (3)$$

Where A_s [m^2] is the rear surface area from the baking plate, F_{bp} [-] is the view factor from the burner to the baking plate. The total radiative flux leaving the burners is J_b [W/m^2] and total radiative flux leaving the rear baking surface of the plate is J_p [W/m^2]. Therefore,

$$\dot{q}_{rad} = \dot{q}_{bp} = A_s F_{bp} \sigma\left(T_b^4 - T_p^4\right) \quad (4)$$

Where $\dot{q}_{bp}$ [W] is the radiation net rate that leaves the burners and goes to the baking plate, σ is the Stephan-Boltzmann constant with the value 5.67x10^{-8} [W.m^{-2}.K^{-4}]. The temperature of the flame on burner T_b [K] and T_p [K] is the local temperature of the rear of the baking plate. The view factor depends of the geometry of the radiation of the burner and the baking plates, and it can be seen as the radiation from burner that is intercepted by baking plate, which means:

$$F_{bp} = \frac{radiation\ leaving\ burner\ A_b\ and\ hitting\ the\ plate\ A_p}{total\ radiation\ leaving\ the\ burner\ A_b} \quad (5)$$

In simulation software the surfaces are divided into facets in the meshing geometry, the parts were drafted in a CAD software to be faster and imported into the simulator. The view factor is computed internally by COMSOL, using a hemicube model.

The radiant net exchange q_{rad} [W] in which the radiation leaves the burner and arrives in the baking plate can be calculated also by the radiative interactions absorbed and reflected.

$$q_{rad} = A_s\ (J_p - G_p) \quad (6)$$

Equation (7) provides the radiosity, where E_p [W/m^2] is the emissive power of the surface of the plate and ρ_p [-] is the baking surface reflectivity and G_p [W/m^2] is the baking plate irradiation.

$$J_p = E_p + \rho_p G_p \quad (7)$$

which in turn yields:

$$J_p = \varepsilon_{ff}\ E_p + (1 - \varepsilon_{ff})G_p \quad (8)$$

where: ε_{ff} [-] is the emissivity of the cast iron set as 0.67, E_p is the power emissivity of baking plate surface as defined by law of Stefan-Boltzmann:

$$E_p = \sigma\ (T_b^4 - T_p^4) \quad (9)$$

Then the heat transfer net rate from radiation over the rear baking plate is:

$$q_{rad} = \varepsilon_{ff} A_s \frac{E_p - J_p}{(1 - \varepsilon_{ff})} \quad (10)$$

More details of the finite element of heat conduction and other details can be found in COMSOL, 2019.

4. CONSTRUCTAL DESIGN OF THE FINNED SURFACE

The method employed in order to explore design trends is the Constructal Design proposed by Bejan (1996). The model consists of identifying the essential flows of a system, the constraints, the source of imperfections and the degrees of freedom. It is based on the Constructal Law, which is detailed in Bejan and Lorente, 2008 and further discussed by Errera, 2018.

Briefly, there are 5 degrees of freedom for a trapezoidal fin that can be varied in order to generate designs that are tested. The Constructal Law states that the configurations that facilitate the flow the most tend to prevail. In this work, this is translated into the average temperature at the baking side of the plate and its non-uniformity. Some three-dimensional possibilities are modeled to find optimized shape to the heat flux, and the variation of the temperature on the baking surface is analyzed.

The main constraint is the amount of material of the heated surface of the baking plate. For instance, if the material volume is turned into trapezoidal fins, the constraint is given by Eq. (11), based on the indications of Fig. 2.

$$V_{cte} = \left\{N \left[\frac{(W_b + W_f)}{2}\right] h_f + h_p W_p\right\} \mathrm{L} \quad (11)$$

Where, V_{cte} [m^3] is the plate fixed volume, W_b [m] is the width of the fins base, W_f [m] is the width of the tip of the fin, h_f [m] is the height of the fin, h_p [m] is the thickness of the base of the plate, W_p [m] is the width of the base of the plate, and L [m] é a length of the plate in the third dimension. In rectangular fins, $W_b = W_f$. In parabolic fins, the shape is fixed for initial simulations. The geometric parameters (Eq. (11) and Fig. 2) of each configuration (design) are determined in a non-linear algebraic solver implemented in electronic spreadsheet. W_b, W_f and h_f were determined for a fixed condition for h_p while the number of fins, N, varied between 3 e 17. Physical and constructive constraints were taken into account.

The baking plates are supported by tongs, and on them are hinges that allow a precise closure of the plates against each other. When the plates are closed, a pressure chamber is formed, the plates are loaded by the steam pressure from the batter. The load results in an elastic deformation of the baking plates, which is similar to deflection of a beam. A relation between small deformation of the plates and the better heat transfer could be achieved by calculation and graphics and relating to fin numbers. The deformation is calculated by the formula:

$$\delta = \frac{5\,F\,L^4}{384\,E\,J_x} \tag{12}$$

Where, δ [m] is the deformation in the baking plate, F [N] is the force load in the baking plates due the steam pressure, E [N.m^{-2}] is the elasticity module of the cast iron, J_x [m^4] is the inertia moment of the cross section of the baking plates. The baking pressure is around 700 [kPa] due the saturation of the water in a temperature of 170 ºC, the elasticity module for cast iron was considered to be E = 137×10^9 [N.m^{-2}], and the inertia moment in a cross section was found through the design of each shape and fin number by computer aided design using toll mass properties

5. RESULTS AND DISCUSSION

Even though the temperature of the baking is variable during the process, we consider the process steady as an initial approach. Was used a thermographic camera model FLIR E4 to shoot images the oven and validate the temperatures used during the baking. The emissivity adjusted for reading was ε = 0.95 relative to cast iron, rough and oxidized, like the baking plates into the oven (Howell, 2011). The measurement of the baking plates temperatures during operation shows that the temperature for baking is around 170 °C and 180 °C, as informed before by the Wafer Handbook Manual. Therefore, the energy supplied by the burners must be enough to reach such temperature. In the specification sheets the accuracy is expressed both in percentages and degrees Celsius. The measured temperature might vary from the actual temperature with either the mentioned percentage or absolute temperature the measurement uncertainty ±1 % or ±1 °C. That demonstrates the observed temperature in an industrial scale oven in normal conditions of work the temperature range is used correctly.

The simulations reached temperature level found in thermographic measurements in real operational baking plates (Fig. 4). So far, it was no possible to perform and thorough comparison between simulation and real.

From a previous work (Carzino et al., 2019) we compared a finned surface with a plain rectangular plate with the same volume. That showed a finned surface performs better. In Fig. 5 we show the temperature profile along the width of the baking surface of the plate for trapezoidal fins for different numbers of fins, N. Higher temperatures of the baking surface are reached with larger number of fins. Temperature non-uniformity seems however unavoidable since the finned surfaces are not irradiated uniformly neither the thermal resistance of the plate is uniform.

The view factor from the burner to the fins increases with the number of fins. On the other hand, when we add material to the plate, we increase its weight and consequently increase the production costs. The trade-off is then to increase the number of fins in the plate and keep the plate weight constant, so there should be a design in which the plates have as many fins as possible, does not lose mechanical strength and transfers as much heat as possible.

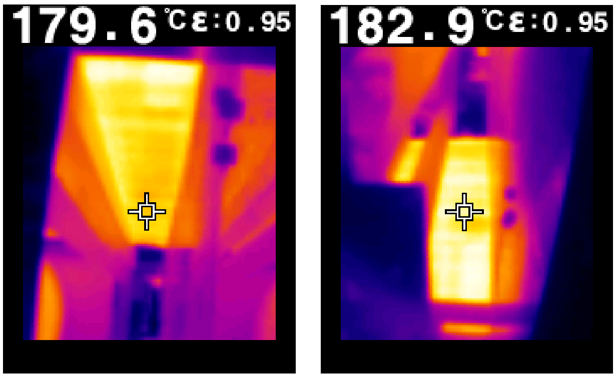

Figure 4. Thermographic images from the actual baking plates during operation, on left side the top baking plate shows 179.6 °C and on right side the bottom baking plate shows 182.9 °C, the emissivity adjusted to measure was 0.95. (Source: The Autor)

In the specification sheets the accuracy is expressed both in percentages and degrees Celsius. The measured temperature might vary from the actual temperature with either the mentioned percentage or absolute temperature the measurement uncertainty ±1 % or ±1 °C. That demonstrates the observed temperature in an industrial scale oven in normal conditions of work the temperature range is right used.

Figures 5 to shows the baking surface temperature increasing with the number of the fins, that is, the more fins are arranged on the plate the higher the surface baking temperature for trapezoidal shapes. A somewhat different trend is observed in Fig. 6 with the hexahedron shapes, but with higher average temperature and better temperature distribution.

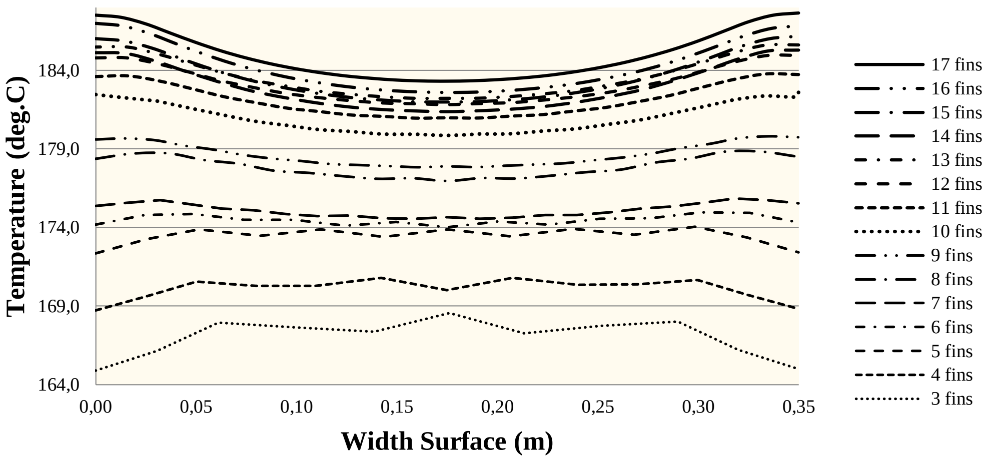

Figure 5. Temperature profile along the width of the baking surface of the plate for trapezoidal shape for different numbers of fins, N. (Source: The Autor)

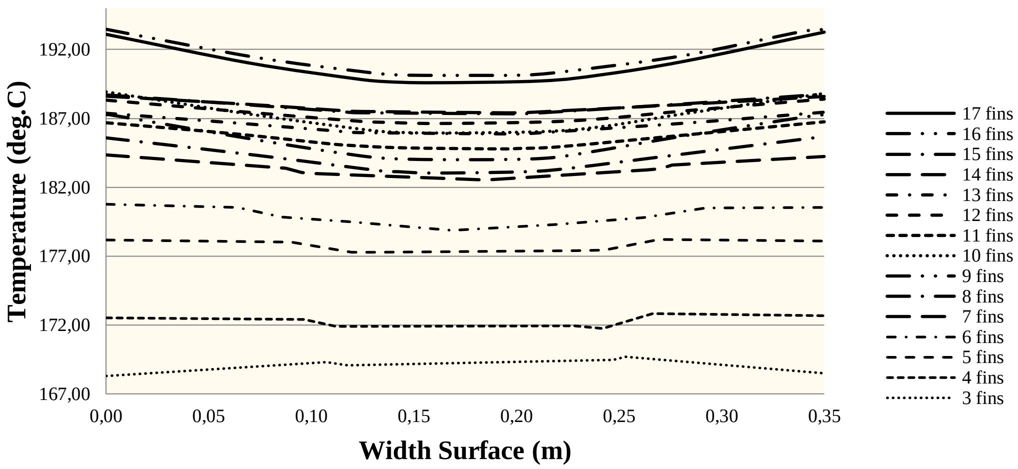

Figure 6. Temperature profile along the width of the transversal baking surface of the plate for hexahedron shape for different numbers of fins, N. (Source: The Autor)

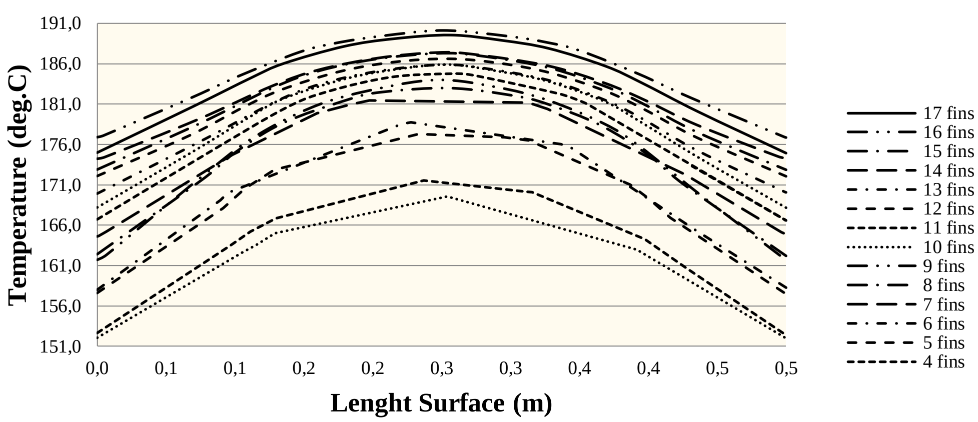

Figure 7. Temperature profile along the width of the longitudinal baking surface of the plate for hexahedron shape for different numbers of fins, N. (Source: The Autor)

Figure 7 shows the temperature profiles along the longitudinal direction of the same shapes showed in Fig. 6, which indicated an important temperature variation from the center to the edges.

Figure 8 shows the consolidation of the average temperature of all shapes simulated. Overall the plates with hexahedron shapes perform better that all the other shapes. Figure 9 shows the maximum deformation observed for each design. Sturdiness performance was not obvious as thermal performance.

The trade-off between the mechanical and thermal performance is summarized in Fig. 10 where deformation and average temperature are plotted in pairs for each configuration. The better trade-off is found in the upper left area for the graph.

Figure 11 shows the different models of baking plates by computational software with mesh simulation for plates with 14 rows of fins with triangular, rectangular, trapezoidal, truncated cone, pyramidal and hexahedron formats.

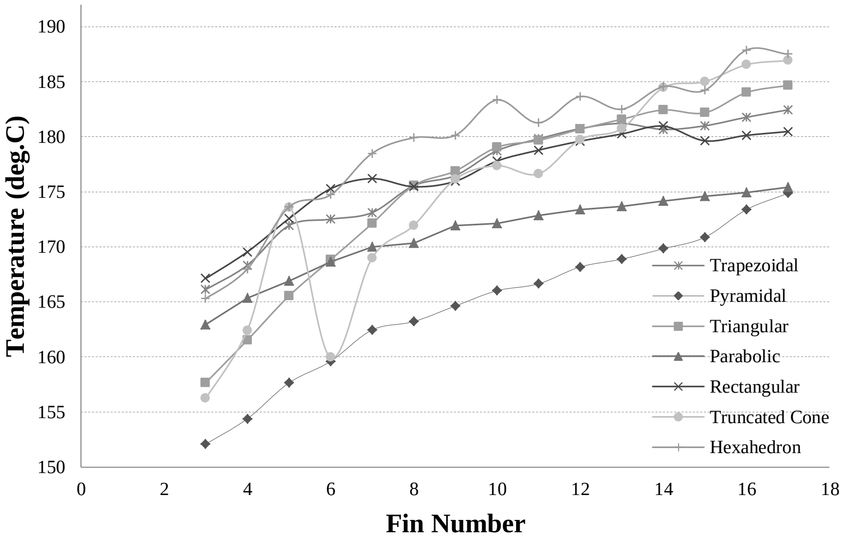

Figure 8. Average baking surface temperature of the plate finned with variable number of geometric. (Source: The Autor)

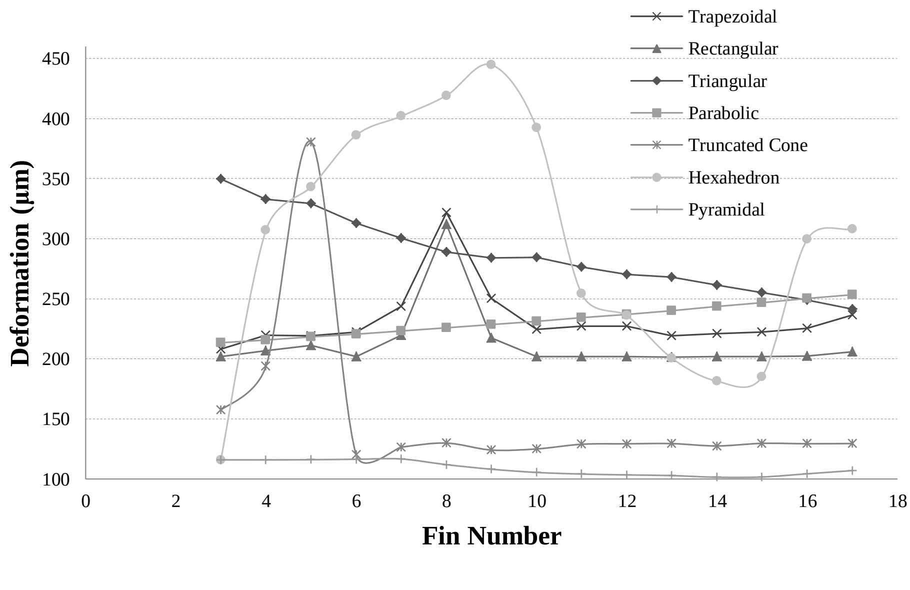

Figure 9. Deformation of the plate due baking pressure. (Source: The Autor)

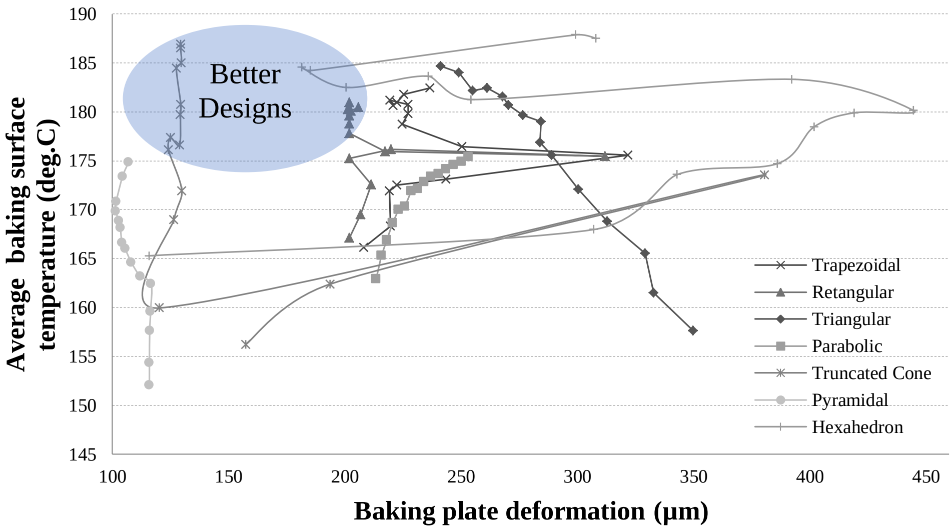

Figure 10. Trade-off baking plate deformation versus average baking surface temperature. (Source: The Autor)

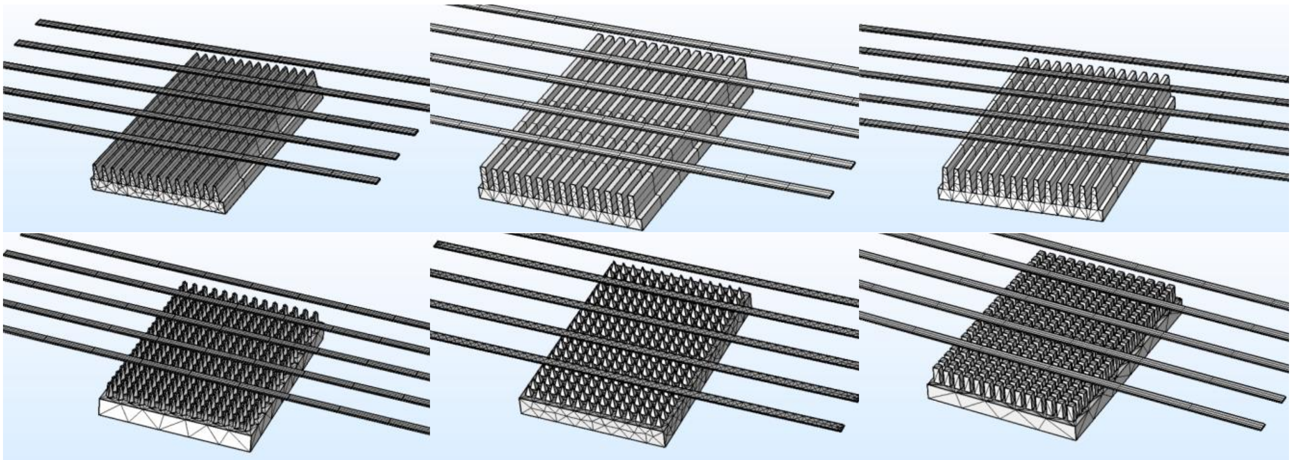

Figure 11. Mesh simulation of plates with 14 rows of: triangular, rectangular, trapezoidal, truncated cone, pyramidal and hexahedron fins. (Source: The Autor)

6. CONCLUSIONS

This paper explores the design possibilities of baking plates for wafer. The design of those plates must consider a trade-off of mechanical resistance (low deformation), performance (higher temperature for a given heat flux) and temperature uniformity for quality purposes.

The numerical model was simple enough to sense how the main features of the design affects the project criteria set forth.

The method of Constructal Design provided a landscape of possibilities that will aid project engineers to choose the configurations that meet the goals when manufacturing, operational and economic issues are later addressed.

The simulations showed that for all configurations tested there remained a more heated sector in the middle of the plate which affects the quality of the product.

In sum the new designs provide better heat transfer that in turn decreases the baking time, while it also improves heat distribution thus warranting product quality. Furthermore, the new designs provide the same mechanical resistance with less 17% material. The simulations with 3-D baking plates show that with the same power supplied to plates with 3 fins to 17 fins can reach a baking temperature 18% higher from the average temperature of all plates. That is a promising result for great improvements in the design.

This paper showed that the best shapes are the ones with truncated cones and pyramids since the provides the higher average temperature with lower nonuniformity while showing the least deformation.

This work moves forward the research for design improvements in wafer baking plates even though it was carried out with simplifying assumptions.

7. ACKNOWLEDGEMENTS

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