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The physics of baking good pizza

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Abstract

Physical principles are involved in almost any aspect of cooking. Here we analyse the specific process of baking pizzas, deriving in simple terms the baking times for two different situations: for a brick oven in a pizzeria and a modern metallic oven at home. Our study is based on fundamental thermodynamic principles relevant to the cooking process and is accessible to undergraduate students. We illustrate the underlying physics by some simple common examples and then apply them in detail to the example of baking pizza.

 Supplementary material for this article is available [online](#)

Introduction

Pizza is one of the most popular foods in the world and has a long tradition and history (a brief overview can be found in the supplementary information (stacks.iop.org/PhysEd/53/065011/mmedia)). However, despite its apparent simplicity, it proves to be quite challenging to produce a delicious pie. The main question we address here is, why pizza in a pizzeria is so much better than what you can produce at home in an electric oven by analyzing the cooking processes in both cases in detail.

Being curious and pizza aficionados, the authors began looking into the secrets of making a perfect pizza. Rule number one, as Italians told them, was to always look for a pizzeria with a wood-fired oven (not an electrical one). Good pizzerias are proud of their 'forno' ('oven' in Italian), in which you can see with your own eyes the entire process of baking. The *pizzaiolo* (pizza-baker) forms a dough disc, covers it with toppings, places the fresh pizza on top of a wooden

or aluminum peel, and finally transfers it into the oven. A couple of minutes later it is sitting in front of you, covered with mouth-watering bubbles of cheese, encouraging you to consume it and wash it down with a pitcher of good beer.

The authors received useful advice from a friendly *pizzaiolo* who was working in a local Roman pizzeria (figure 1), frequently visited by them when they lived in that neighborhood: 'Always come for a pizza either before 8 p.m. or after 10 p.m., when the pizzeria is half-empty'. The advice was also confirmed by one of the pizzeria's frequent visitors: a big grey cat. When the pizzeria was full, the cat would leave, and did not show any interest in what was on the patron's plates.

The reason for this advice was very simple—oven capacity. As the *pizzaiolo* explained,

⁵The optimal temperature depends somewhat on the consistency of the dough, changing its physical properties, see table 1.

325 °C–330 °C⁵ is the optimal temperature for Roman pizza baked in a wood-fired oven with fire-brick bottom. In this case, a thin Roman pizza will be done in 2 min. Thus, even putting two pizzas into the oven at a time, the pizzaiolo can serve 50–60 clients within an hour. During peak hours, about one hundred customers frequent the pizzeria per hour and at least ten clients are waiting for a take-out pizza. To meet the demand, the pizzaiolo increases the temperature in the oven up to 390 °C, and pizzas ‘fly out’ of the oven every 50 s (hence, each one requires a baking time of around 1½ min). However, their quality is not the same: the bottom and the crust are a little ‘overdone’ (slightly black), and the tomatoes are a little undercooked.

Since it is not always easy to find a pizzeria with a brick oven, let us look what advantages it has compared to an electric oven and whether there is a way to use the latter to produce a decent pizza.

To illustrate the physical principles involved in baking pizzas, let us consider a common example of how heat is transferred. Imagine when you were a child and had a fever, but no thermometer at hand. Your mother would put her hand on your forehead and quickly say: ‘you have a high temperature, no school for you tomorrow’. To investigate this process scientifically, we start with simplifying the problem: Let us imagine that your mom is touching your forehead with her own forehead rather than her hand. In that case, if the temperature of your forehead would have been 38 °C, and your mother’s 36 °C, it is clear by the symmetry of the problem that the temperature at the interface (T_0) between the two foreheads will be 37 °C, and that your mother would feel the flow of heat coming from your forehead (the actual temperature distribution in time is shown in figure 2).

Now let us assume that your head is made of steel, with the same temperature—38 °C. Intuitively, it is clear the temperature at the interface will increase, in this case to 37.7 °C. This is related to the fact that the steel will ‘deliver’ more heat to the interface region from its bulk, since its heat conductivity is larger (an illustration is shown in figure 3).

Let us now analyze the process of pizza baking more scientifically. In contrast to the above example to illustrate the concept of interface temperature, the pizza ‘system’ is more complicated as it consists of a (bulk) oven and only

thin layers of dough and toppings, which all three must be considered when analyzing the cooking process, involving the process of boiling water as well. Note, that for the following analysis we consider a horizontal arrangement, i.e., the oven is on the left (as the child’s head) and the pizza on the right (like mother’s hand or head).

Heat transfer

We start by reminding the reader of the main concepts of heat transfer [1]. When we talk about ‘heat’, we usually have in mind the energy of a body (like the child’s head, the oven, or the pizza itself) associated with the chaotic motion of atoms, molecules and other particles it is composed of. We inherited this concept of heat from the physics of a past era. Physicists say that heat is not a function of the state of a system, but rather that its amount depends on the way the system achieved this state. Like work, heat is not a type of energy, but a value convenient to use in describing energy transfer [2, 3]. The amount of heat, necessary to raise the temperature of a mass unit of the material by one degree, is called a specific heat capacity of the material:

$$c = \frac{\Delta Q}{M\Delta T}. \quad (1)$$

Here M is the mass of the system and ΔQ is the quantity of heat required for heating the system by a temperature ΔT . From this expression it is clear that the heat capacity is measured in $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ in SI units.

In the case of a thermal contact between the two bodies with different temperatures, the heat will go from the warmer body to the cooler one. The heat flux density q is the amount of heat ΔQ that flows through a unit area per unit time in the direction of temperature change:

$$q = \frac{\Delta Q}{S\Delta t}. \quad (2)$$

In the simplest case of a homogenous non-uniformly heated body, using equation (1), one finds

$$q = \frac{cM\Delta T}{S\Delta t} = c\rho \frac{(\Delta x)^2}{\Delta t} \left(\frac{\Delta T}{\Delta x} \right) = -\kappa \frac{dT}{dx}, \quad (3)$$

⁶ One can also use this formula to easily find the heat loss through the walls of one’s house during a cold winter. In this stationary situation, the temperature distribution does not change with time.



Figure 1. Two modern pizzaiolos in Rome in front of a brick pizza oven and pizza Margherita.

where ρ is the mass density⁶. Assuming that Δx is small, we identified the value in parentheses as the derivative of the temperature by the coordinate x and considered the fact that the temperature decreases in x -direction (see figure 4). In the general case, \mathbf{q} is a vector and the derivative in equation (3) is replaced by the gradient ∇T , which describes the rate of temperature change in space. The coefficient κ in equation (3) is the thermal conductivity, which describes the ability of a material to transfer heat when a temperature gradient is applied⁷. Equation (3) expresses mathematically Fourier’s law, which is valid when the temperature variation is small.

Next, let us analyze how a ‘temperature front’ penetrates a medium from its surface, when a heat flow is supplied to it (see figure 4). Assume that during time t the temperature in the small cylinder of the length $L(t)$ and cross-section S has changed by ΔT ⁸. Let us get back to equation (3) and rewrite it by replacing Δx by $L(t)$:

$$\frac{c\rho L(t) \Delta T}{t} = \kappa \frac{\Delta T}{L(t)}. \quad (4)$$

Solving equation (4) with respect to the length $L(t)$ one finds:

⁷The definition of the thermal conductivity $\kappa = c\rho \frac{(\Delta x)^2}{\Delta t}$ used in equation (3) requires clarification: While our simplified derivation suggests a geometry dependence, we emphasize that in reality it is determined only by microscopic properties of the material.

⁸This process is not stationary anymore and the flow q is not constant, since the heat will be partially used for the heating of the cylinder material. Therefore, unlike in the stationary process, the rate of temperature change dT/dx in the medium is a function of space and time.

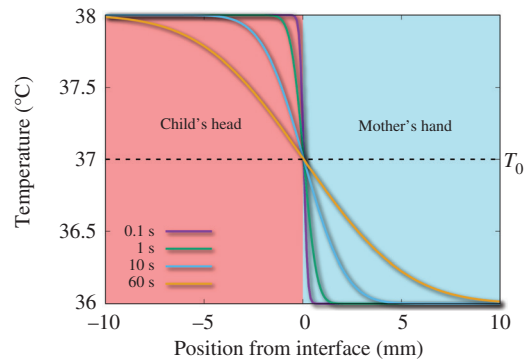


Figure 2. Temperature profile within child’s head and mother’s hand or head- 0.1 s, 1 s, 10 s, and 60 s after they made contact.

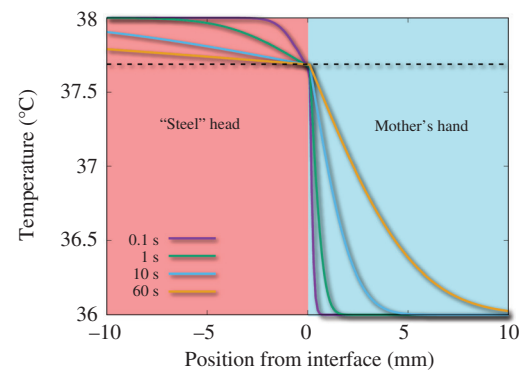


Figure 3. The same as figure 2, but with a steel ‘head’.

$$L(t) \sim \sqrt{\frac{\kappa t}{c\rho}} = \sqrt{\chi t}, \quad (5)$$

i.e. the temperature front enters the medium by a square-root law of time. The time after which

the temperature at distance L from the interface will reach a value close to the one of the interface depends on the values of κ , c , and ρ . The parameter $\chi = \kappa/c\rho$ is called the thermal diffusivity or coefficient of temperature conductivity and the heating time of the whole volume can be expressed in its terms: $\tau \sim L^2/\chi$.

Of course, our consideration of the heat penetration problem into a medium is just a simple evaluation of the value $L(t)$. A more precise approach requires solution of differential equations. Yet, the final result confirms our conclusion (5), just corrected by a numerical factor:

$$L(t) = \sqrt{\pi\chi t}. \quad (6)$$

Now that we know how heat transfer works, let us get back to the problem of calculating the temperature at the interface between two semi-spaces: on the left with parameters κ_1 , c_1 , ρ_1 and temperature T_1 at $-\infty$, and on the right with parameters κ_2 , c_2 , ρ_2 and temperature T_2 at $+\infty$. Let us denote the temperature at the boundary layer as T_0 . The equation of energy balance, i.e. the requirement of equality of the heat flowing from the *warm*, left semi-space through the interface to the *cold*, right semi-space, can be written in the form

$$q = \kappa_1 \frac{T_1 - T_0}{\sqrt{\pi\chi_1 t}} = \kappa_2 \frac{T_0 - T_2}{\sqrt{\pi\chi_2 t}}. \quad (7)$$

Here we simplified the problem assuming that all temperature changes happen at the corresponding time dependent length (6). Solving this equation with respect to T_0 one finds that

$$T_0 = \frac{T_1 + \nu_{21}T_2}{1 + \nu_{21}}, \quad (8)$$

where

$$\nu_{21} = \frac{\kappa_2}{\kappa_1} \sqrt{\frac{\chi_1}{\chi_2}} = \sqrt{\frac{\kappa_2 c_2 \rho_2}{\kappa_1 c_1 \rho_1}} \quad (9)$$

One notices, that time does not enter in expression (8) (i.e. the interface temperature remains constant in the process of the heat transfer, see figures 2–5). In the case of identical media with different temperatures one can easily find: $T_0 = \frac{T_1+T_2}{2}$. This is the quantitative proof of the intuitive response we provided in the beginning of the article for the temperature of 37 °C at the interface between the mother’s hand and the

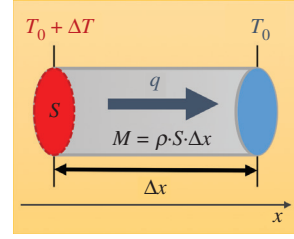


Figure 4. Heat flow in a small cylinder from hot ($T_0 + \Delta T$) to cold (T_0). Notice, the temperature decreases from left to right!

child’s forehead. If the child’s head would be made of steel, $\nu_{21} \ll 1$ and $T_0 \approx T_1$, the interface temperature would be much higher, meaning that the child’s fever would feel higher.

Finally, we are ready to discuss the advantages of the brick oven. Let us start from the calculation of the temperature at the interface between the pizza placed into the brick wood-fired oven (*wo*) and its heated baking surface. All necessary parameters are shown in table 1.

Assuming the initial temperature of the pizza dough (*do*) as $T_0^{\text{do}} = 20$ °C, and the temperature inside the oven—as our pizzaiolo claimed—being about $T_1^{\text{wo}} = 330$ °C, we find for the temperature at the boundary layer between the oven surface and pizza bottom

$$T_0^{\text{wo}} = \frac{330 \text{ °C} + 0.65 \cdot 20 \text{ °C}}{1.65} \approx 208 \text{ °C}.$$

As we know from the words of the same pizzaiolo, a pizza is perfectly baked in 2 min under these conditions.

Let us now repeat our calculations for the electric oven with its baking surface made of steel. For an electric oven the ratio will be $\nu_{\text{eo}} = 0.1$, and if heated to the same temperature of 330 °C, the temperature at the bottom of the pizza will be equal to

$$\frac{330 \text{ °C} + 0.1 \cdot 20 \text{ °C}}{1.1} \approx 300 \text{ °C}.$$

That is too much! The pizza will just turn into coal! This interface temperature is also much higher than in Naples’ pizzerias, where oven temperatures between 400 °C–450 °C are common.

Well, let us formulate the problem differently. Let us assume that generations of pizza makers, who were using wooden peels to transfer pizzas

Table 1. Physical properties of different materials, including heat capacity, thermal conductivity, density and temperature conductivity.

Property/Material	Heat capacity c [J · (kg · K) ⁻¹]	Thermal conductivity κ [W · (m · K) ⁻¹]	Mass density ρ [kg · m ⁻³]	Temperature conductivity χ [m ² · s ⁻¹]	ν_{21} ⁹
Dough ¹⁰	2–2.5 × 10 ³	0.5	0.6–0.8 × 10 ³	2.5–4.2 × 10 ⁻⁷	1
Food grade steel (<i>X18H10T</i>)	4.96 × 10 ²	18	7.9 × 10 ³	4.5 × 10 ⁻⁶	0.1
Fire brick	8.8 × 10 ²	0.86	2.5 × 10 ³	4.0 × 10 ⁻⁷	0.65
Water (@25C)	4.2 × 10 ³	0.58	1.0 × 10 ³	1.4 × 10 ⁻⁷	0.2

into the oven, are right: the temperature at the (Roman) pizza’s bottom should be about 210 °C. What would be the necessary temperature for an electric oven (eo) with steel surface?

The answer follows from equation (8) with coefficient $\nu_{eo} = 0.1$ and solved with respect to T_1^{eo} when the temperature at the bottom of the pizza is the same as in the wood oven: $T_0^{eo} = T_0^{wo}$. The result of this exercise shows that the electric oven should be much colder than the brick one: $T_1^{eo} \approx 230$ °C.

It seems that if one could disregard the flavor of burning wood, the sizzling dry air in the brick oven and other natural features, the problem would be solved: We just set the electric stove controls to 230 °C and in a couple of minutes we can take an excellent pizza out of the oven. But: is it that easy?

Thermal radiation

To answer this question, we first need to consider the second important mechanism of a heat transfer: *thermal radiation* [4]. Its intensity, the amount of radiation energy arriving each second to 1 cm² of surface in the oven, is determined by the Stefan–Boltzmann law:

$$I = \sigma T^4, \tag{10}$$

where $\sigma = 5.67 \cdot 10^{-8} \text{ W} \cdot (\text{m}^2 \cdot \text{K}^4)^{-1}$ is the so-called Stefan–Boltzmann constant.

A typical brick oven has a double-crown vault filled with sand, which is kept at almost constant temperature. Its walls as well as the bottom

⁹ For dough, steel, and brick, material ‘2’ is dough. For water, material ‘1’ is steel.

¹⁰ The material parameters for dough should be considered as an estimate. It is clear that the exact numbers strongly depend on the type of flour and the fermentation/rising time of the dough (in the latter process, the dough is enriched by gases, which change its density).

part, are also heated to $T_1^{wo} = 330$ °C = 603 K, meaning that the complete volume of the oven is ‘filled’ by infrared radiation. With a temperature that high, this radiation becomes significant: a pizza in this oven is continuously ‘irradiated’ from both sides by a ‘flow’ of infrared radiation of intensity

$$I^{wo} = \sigma(T_1^{wo})^4 = 5.67 \cdot 10^{-8} (603)^4 = 7.5 \text{ kW} \cdot \text{m}^{-2},$$

i.e. each second an amount of energy close to the 0.75 J arrives at 1 cm² of pizza¹¹.

Here one should notice, that, in its turn, the pizza also irradiates out a ‘flow’ of the intensity $I_{\text{pizza}} = \sigma(T_{\text{pizza}})^4$. Since the major part of the baking time is required for the evaporation of water contained in the dough and toppings, we can assume $T_{\text{pizza}} = 100$ °C = 373 K, since the toppings will boil at this temperature till they (and the whole pizza) are well cooked, which results in a radiation intensity of $I_{\text{pizza}} = 1.1 \text{ kW} \cdot \text{m}^{-2}$, i.e. 15% of the obtained radiation, the pizza ‘returns’ back to the oven.

For the much less heated electric oven, the corresponding amount of energy, incident to 1 cm² of pizza surface, is less than half:

$$I^{eo} = \sigma(T_1^{eo})^4 = 5.67 \cdot 10^{-8} \frac{(503)^4 \text{ W}}{\text{m}^2} = 3.6 \text{ kW} \cdot \text{m}^{-2},$$

while the returned radiation is the same: 1.1 kW · m⁻².

Now it is a time to evaluate what amount of heat 1 cm² of pizza receives per second through its bottom. By definition it is determined by the heat flow (3) and to get its numeric value, we will evaluate the temperature gradient at the oven surface in the same way as was done in equation (7):

¹¹ Here we assume that the pizza behaves as a black body. In reality it is slightly reflective, reducing the amount of heat it absorbs.

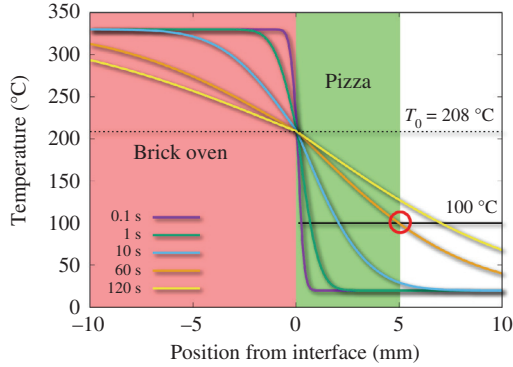


Figure 5. Temperature profile in a brick oven with pizza at different times. At 60 s the top surface of the pizza reaches 100 °C (red circle). Here we only take thermal diffusion into account. Evaporation and radiation are neglected.

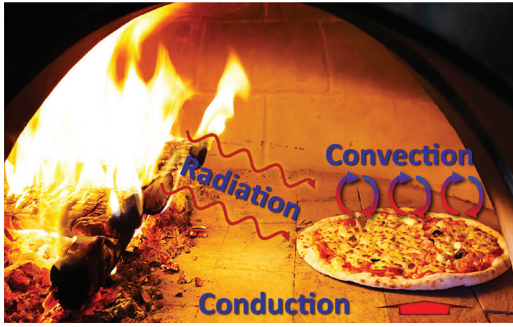


Figure 6. Heat transfer mechanisms in the pizza oven.

$$q(t) = \kappa \frac{T_1^o - T_0}{\sqrt{\pi \chi t}},$$

where T_1^o is the temperature of the oven. One can see, that, contrary to the Stefan–Boltzmann radiation, the heat flux arriving into the pizza by means of a heat conductance depends on time. Correspondingly, the amount of heat transferred to 1 cm² of pizza from the oven during time τ is determined by

$$Q(\tau) = \int_0^\tau q(t) dt = 2\kappa (T_1^o - T_0) \sqrt{\frac{\tau}{\pi \chi}}.$$

Therefore, the total amount of heat, arriving at 1 cm² of pizza during time τ , is

$$Q_{\text{tot}}(\tau) = \sigma [(T_1^o)^4 - (T_{\text{pizza}})^4] \tau + 2\kappa (T_1^o - T_0) \sqrt{\frac{\tau}{\pi \chi}}. \quad (11)$$

This value is used to heat 1 cm² of pizza from the raw pizza temperature $T_2^{\text{do}} = 20^\circ\text{C}$ to T_{pizza} :

$$Q_{\text{heat}} = c^{\text{do}} \rho^{\text{do}} d (T_{\text{pizza}} - T_2^{\text{do}}).$$

Yet, this is not all. During the process of baking the perfect pizza we apparently evaporate water from the dough, tomatoes, cheese, and other ingredients. We need to take the required energy for this into account as well. If one assumes that the water mass fraction α evaporates from the dough and all topping one gets:

$$Q_{\text{boil}} = \alpha L \rho^{\text{water}} d.$$

Here d is the thickness of the pizza, which we assume to be $d = 0.5$ cm, while $L = 2264.76 \text{ J} \cdot \text{g}^{-1}$ is the latent heat of evaporation for water.

Collecting both these contributions in one, we can write

$$Q_{\text{tot}} = Q_{\text{heat}} + Q_{\text{boil}} = c^{\text{do}} \rho^{\text{do}} d (T_{\text{pizza}} - T_2^{\text{do}}) + \alpha L \rho^{\text{water}} d. \quad (12)$$

Equating equations (11) and (12) one finds the final equation determining the ‘baking time’ of pizza:

$$\begin{aligned} \sigma [(T_1^o)^4 - (T_{\text{pizza}})^4] \tau + 2\kappa (T_1^o - T_0) \sqrt{\frac{\tau}{\pi \chi}} \\ = c^{\text{do}} \rho^{\text{do}} d (T_{\text{pizza}} - T_2^{\text{do}}) + \alpha L \rho^{\text{water}} d. \end{aligned} \quad (13)$$

Final baking time calculation

To obtain a realistic answer for the baking time, it is important to know the amount of water which is evaporated during the baking process. A typical recipe for pizza Margarita calls for 240 g of dough and 90 g of toppings (consisting of tomatoes and mozzarella). The dough contains about one-third of water and the toppings 80% (the rest is mostly fat from the cheese). Together with a weight loss of 30 g, a good assumption is a 20% loss of water, i.e. $\alpha = 0.2$. Using this with the values of specific heat capacity and density for dough from table 1, one finds that $Q_{\text{tot}} = (70 + 226) \text{ J} \cdot \text{cm}^{-2}$, which gives for the baking time in the wood oven $\tau_{\text{wo}} \approx 125$ s. For the electric oven an analogous calculation results in an almost 50% longer time $\tau_{\text{eo}} \approx 170$ s. We see that we have succeeded in reproducing the value disclosed to us by our pizaiolo: 2 min for baking in a wood oven. The result of an attempt to bake a pizza in an electric oven will be the mentioned unbalanced product.

Using equation (8) one can easily find that the temperature at the interface between the pizza and oven surface reaches 240 °C, when the temperature in the wood-fired brick oven increases to 390 °C. Replacing correspondingly T_0 in equation (13) one can find the baking time under these extreme conditions to be approximately 82 s. Hence, the productivity of the oven increases by almost 50%!

A final ‘secret’ disclosed to us is important for pizzas with water-rich toppings (eggplants, tomatoes slices, or other vegetables). In this case, the expert first bakes the pizza in the regular way on the oven surface, but when the pizza’s bottom is done, he lifts it with the wooden/aluminum peel and holds it elevated from the baking surface for another half minute or more to expose the pizza to just heat irradiation. In this way they avoid burning the dough and get well cooked toppings.

Certainly, as is routinely done in physics, to get to the core of the phenomenon, we examined only the simplest model here (in particular, we ignored the third mechanism of heat transfer: convection, which we can assume to have only a small effect. (See figure 6, which illustrates the essential physical processes).

As a final note, we remark that it is difficult to build a classic brick oven, and many customers do not appreciate the difference between an excellent and decent pizza. These are the reasons why engineers invent all sorts of contraptions to improve the results of pizza baking at home: for example, inserting a ceramic bottom made of special ceramics to imitate the bottom of brick ovens in a modern professional electric oven. To bake a pizza evenly, rotating baking surfaces are available—convection ovens emulate the gas flows in brick ovens, and many other things. But, the dry heat and the smell of wood in traditional firebrick ovens remain the ideal way to bake the perfect pizza.

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