OVENS AND HEAT TRANSFER - review

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Abstract: *The Department of Grain Science and Industry at Kansas State University, Manhattan, KS, USA, is unique. We offer BS, MS, & PhD degrees in the Science, Technology, & Management of Flour Milling, Feed Milling, and Baking as well as conducting teaching and research in basic Cereal Science. We are involved in post-harvest technology, including grain storage and processing. We take the grains from the farm gate to the consumer's shelves.*
My paper review is about one aspect of the work that my group has been engaged in at various times for the past 20 years: baking ovens and heat transfer. Many other scientists and engineers have contributed to this field as well. However, my intent is to tell you about some of our work, not to provide a comprehensive review of the field, which would take far more time & space than I have available today. Hence, most of the research information which I present is from my laboratory and was performed by my students.

Key words: *baking ovens, heat transfer, thermal radiation, humidity, cakes*

The History of Baking & Ovens The history of ovens and baking actually precedes recorded history. Nomadic prehistoric man had no time for plant cultivation as we know it today, so grass seeds were simply something that he gathered and chewed. Slowly, and by a process about which we can only speculate, mankind learned to remove the husks, parch the grains, make porridges, stumbled across fermentation, and eventually to make flat breads not unlike those yet eaten in many parts of today's world.

The ancestral ovens were flat rocks in the midst of a fire, eventually replaced by clay pots with heat applied all around. By 1000 B.C.E., the Greeks, soon to be followed by those wonderful Roman engineers, developed the basic concept of ovens which would remain unchanged for nearly 2000 years. Yet today, people somewhere in this world are baking their breads in beehive-shaped hearth ovens. Up until only about 100 years ago, even in the industrialized nations, although the ovens got larger, they were still baking breads on a heavy stone hearth, manually loading and unloading them with long-handed peels. The turn of the century development of mechanization brought the full circle 'round, from the slaves of antiquity to the guilded craftsmen of the middle ages, and back to the mechanical slaves (mechanized ovens) and those who slaved before them no less than did the inhabitants of ancient Egypt.

Bakers Needed to Control Their Ovens Bakers have long known that several factors are important in operating an oven to produce the desired baked food characteristics. They have continually searched for cleaner, faster, more uniform, and cheaper baking methods but their choices have been limited to traditionally used technology and controls. Time and temperature could be controlled to an extent, but the rest of the factors which affect baking were largely uncontrollable, in part because they could not measure them. The simple flat rock amidst hot coals relied on direct conduction to heat the relatively thin sheet of dough. Maybe it was burned on the bottom & covered with charcoal on the top, but it was tasty. Then the primitive baker advanced to a clay pot that could be buried in the coals. Then they advanced to a beehive oven, and suddenly they had more control over the time & temperature with a more uniform heat. Not only was heat transferred in from the hot stone hearth, but the hot walls could radiate onto the baking brad, and some circulation of flame, smoke, and hot gases about the product were always present, though uncontrolled, and could carry heat as well, but not until the advent of oven mechanization at the turn of the 20^{th} century did convection begin to be appreciated for the power it passed.

Things That Could Be Controlled By the time that ovens had reached the large peel style and automation was developing, bakers understood the need for time & temperature controls, and had developed methods to use them. They also recognized that all heat was not the same, and that two ovens at the same temperature could still bake differently. Transport efficiency, or the Heat Transfer Coefficient, could not yet be accurately measured, so oven design remained an art. Likewise, they began to install dampers to control the flow of gasses through the oven, and begin to realize that the humidity level was important, but they were even less able to measure humidity inside an operating oven.

Review Heat Transfer Principles

A) From the viewpoint of the scientist or engineer, there are at least eight ways to heat food. The first four involve a source of thermal energy that is at a higher temperature than the food, hence providing a 'driving temperature'. The heat must transfer to the food across a surface.

- Conduction (direct contact)
- Radiation (no transfer media)
- Convection (circulating fluids)
- Condensation of Steam (steam pipe effect)

In the other four methods, the food itself acts as the heating element by absorbing the energy directly.

- Microwaves (molecular vibrations)
- Radio Waves (capacitative heating)
- Ohmic (electrical resistance heating)
- Sonic (mechanical vibrations)

Conduction. When an object is "hot", its molecules (or atoms) are vibrating rapidly, and the hotter it is, the more the molecules vibrate. If a warm object is placed in physical contact with a cooler object, the molecular vibrations are transferred, and the cooler object will continue to warm-up until the two objects reach equilibrium at the same temperature.

The quantity of heat that is transferred by conduction is a function of several factors,

$$Q = k\,(T_H - T_C)\,A\,t\,/\,d \qquad (1)$$

when Q = the quantity of energy transferred,

k = the thermal conductivity coefficient,

T_H = the absolute temperature of the hotter object,

T_C = the absolute temperature of the cooler object,

A = the area across which the heat is conducted,

t = the time during which contact is maintained, and

d = the distance through which the heat must be conducted.

For conventional baking, the value for k may be difficult to estimate because the dough in contact with the hot metal or stone surface will change its properties as it bakes, and k may change in magnitude by a factor of 100 to 1. In fact, the rate of heat transfer in a bread pan usually declines with time as the bread temperature rises (ΔT is reduced) and the bread surface (crust) starts to brown and dehydrate, becoming dryer, more porous, and less conductive. This illustrates the boundary coefficient uncertainty.

Convection. Convection somewhat resembles conduction, except that the heat transfer medium is a circulating fluid. The fluid extracts energy from the hot source & carries it to the colder, where it transfers it. The circulation may be by natural, density induced, means, or it may be forced by fans or pumps. Whereas the circulating fluid is a liquid in the case of frying, it is a gas (air, combustion products, & steam) in the case of baking.

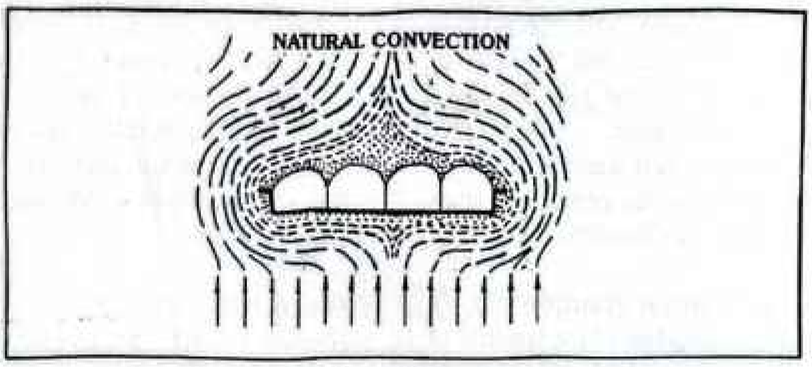


Figure 1 Natural convection

The quantity of heat that is transferred by convection depends upon several factors.

$$Q = h\,(T_H - T_C)\,A\,t \qquad (2)$$

when Q = the quantity of energy transferred,

h = the convective transfer coefficient,

T_H = the absolute temperature of the hotter object,

T_C = the absolute temperature of the cooler object,

A = the area to or from which heat is transferred, and

t = the time during which heating occurs.

This equation closely resembles the conductive transfer equation except that there is not a 'distance' or 'thickness' term, because the fluid is continually moving by the two surfaces. The convective transfer coefficient varies greatly over a range of 40:1 or greater, depending on the fluid velocity and turbulence, as well as its thermal properties. It is very difficult to predict, and until recently could not be easily measured on a routine basis.

Radiation. Thermal radiation is most familiar to us as the sun's rays or the sense we get when we are near a glowing electric or gas heated element in an oven or a space heater. All bodies at a temperature above absolute zero emit IR radiation, and the hotter they are, the more radiation they emit. The rate of radiation is not linear with temperature, however, but rather increases exponentially.

The quantity of heat that is transferred by radiation is more complicated to calculate,

$$Q = \varepsilon\,\sigma\,(T_H^4 - T_C^4)\,A\,t \qquad (3)$$

when Q = the quantity of energy transferred,
ε = the emissive of the surface, from 0 to 1,
σ = the Stefan-Boltzmann constant,
T_H = the absolute temperature of the hotter object,
T_C = the absolute temperature of the cooler object,
A = the area which is 'viewing' the hot object, and
t = the time during which heat transfer occurs.

Radiation occurs 'in both directions', so an object absorbs & radiates at the same time. If it receives more radiation than it emits, then it will heat up. If it emits more than it receives, then it will cool off. Radiation is not a major contributor at lower temperatures, but it begins to become a major factor in baking above about 200 - 250 °C because of the rapid increase as the fourth power of absolute temperature.

Enhanced Convection (Impingement)

A) *Design Concept*

Practically speaking, the heat transfer rates for both conduction and radiation can only be increased by raising the temperature. In the case of convection, however, the fluid velocity and turbulence can be changed as well as the driving temperature. By bringing the fluid into better contact with the solid surface, the efficiency increases. In all cases, it is possible to increase the rate of heat transfer to a surface to the point that it exceeds the ability of the product to absorb it internally, resulting in burning the surface while the inside is still raw & cold.

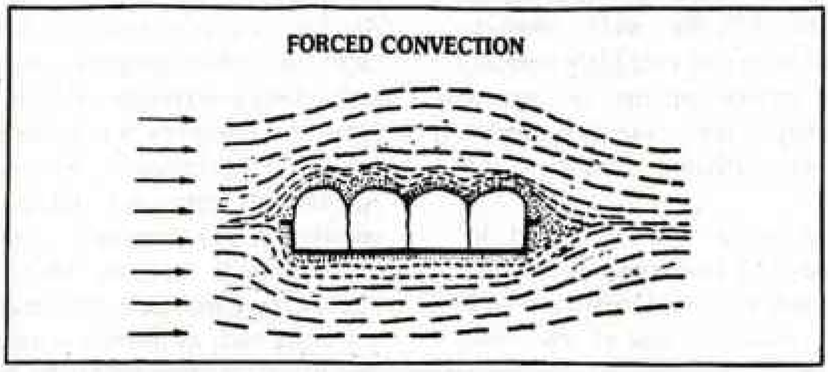


Figure 2 Forced convection

Impingement relies upon the principle of directing a stream of fluid at a very high velocity (10 – 20 meters/sec), **perpendicular** to the surface. The fluid (air, in this case) issues in rather well defined flow patterns from a narrow slit (may be perforated) or from small (1 to 2 cm) diameter tubes, nozzles, or staggered rows of deep-drawn holes. The airflow is usually turbulent (N_{Re} > 2100) and the nozzle pattern is usually arranged to 'sweep' across the surface, requiring that either the air source of the product must be in motion. This provides relatively uniform coverage to avoid burning at certain points. Impingement differs from the conventional 'forced convection' ovens familiar in food service kitchens or the common rotary rack ovens used by retail bakeries. In those, a fan blows air horizontally across the surface of the baking foods at much lower velocities.

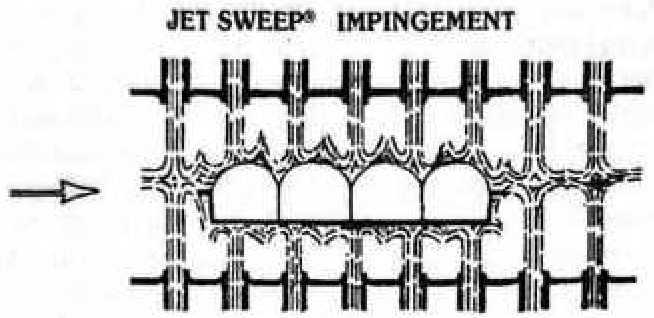


Figure 3 Examples of impingement

A baking food normally has a thin boundary layer of dense, viscous, moist air next to the product. This layer acts as an insulator, preventing the hot circulating air from coming as close in contact with the product as it could otherwise, reducing the rate at which heat can be transferred from the hot air to the cold product. Impingement works so efficiently because the inertial energy of the air stream 'sweeps away' the boundary layer, permitting more efficient exposure to the heat.

A similar principle is widely used in several brands of tube-impinged ready-to-eat (RTE) breakfast cereal toasters, where it is used to fluidize a bed of small-size product pieces.

B) *Measuring the Convective Heat Transfer Coefficient*

It has been almost impossible to accurately predict 'h', the convective heat transfer coefficient based upon information about temperature, velocity, etc. and difficult to accurately measure it for actual baking foods because the conditions are rapidly changing in an oven and in the baking product. The product's shape, size, moisture content, and surface characteristics change rather rapidly during its 5 to 30 min. baking time. While h has been determined experimentally for various products by measuring sensible & latent heat changes during baking, this value is accurate only for that specific product sample in that particular oven. This makes it very difficult to predict the baking conditions in another style of oven, or for scaling-up small production to a larger unit.

Another approach is to use a reference target with known properties, heating it in both ovens and comparing their apparent convective heat transfer coefficients. (This is termed an 'apparent' h-value because adjustments were not made for the radiation, and perhaps conduction, contributions.) Since the baking products will not have the same surface & internal properties such as thermal conductivity as the 'target', the h-value cannot be used in conjunction with the above equation to predict exact baking time by itself, but it can be used to predict probable relative time-temperature changes for a given product being baked in a different oven.

One approach to this 'standardized' reference is to make a target from a metal (AL or CU) plate having high heat capacity and thermal conductivity and with precisely known thickness, diameter, & weight. Mount it in an isolating holder; insert a thermocouple inside the plate center to measure its internal temperature, and provide a thermocouple just away from the surface that can measure the surrounding air temperature. By measuring the rate of target plate temperature rise as a function of its properties and the impinging air temperature, it is possible to calculate the apparent h-value as related to the target plate. The same or similar target plate can then be used in other ovens to compare the relative baking abilities of the various ovens tested, including those with different designs. The relative h-values can then be used to assist in designing or selecting new ovens for the same products.

C) *Impingement Measurements*

1) *Design.* The Enersyst Development Center (EDC) in Dallas, TX, developed the h-Monitor©, a standardized target plate device consisting of two 6-inch (15 cm) diameter aluminum plates in a cast aluminum carrier. A portable data logger (the Super M.O.L.E. ©) from Electronic Controls Design (ECD), Milwaukie, OR, is used to simultaneously record the air temperature and the rising AL target plate temperatures as the device passes through a conveyor oven. By repeatedly setting the heat gained by the plate over a small time interval to be equal to the heat transferred from the air, using the convective transfer equation above, it is possible to solve for the h-value, or convective heat transfer coefficient.

$$Q_{gained} = C_p M \Delta T = Q_{los} = h(T_H - T_C)At \quad (4)$$

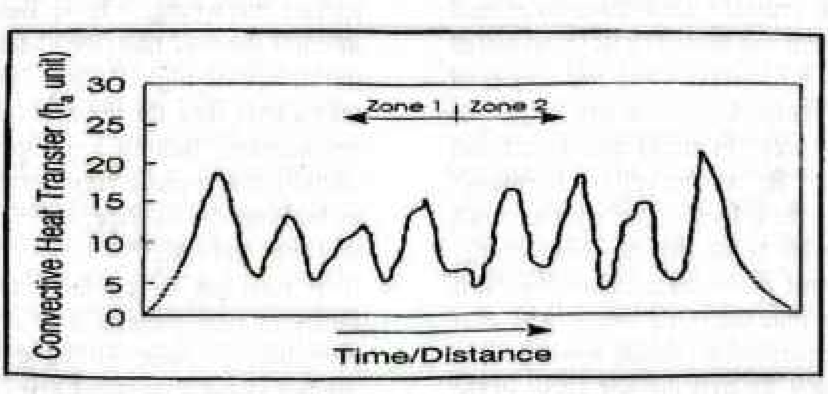
when C_p = the heat capacity (specific heat) of the target plate metal,

M = the mass of the target plate, and

ΔT = the change in temperature of the target plate.

2) *Measurement Results*

This tracing shows the measured heat transfer coefficient as the target plate passed through a two-zone oven, each zone containing four fingers both above & below the conveyor, fitted with nozzles which guide the hot air directly onto the product, or the h-Monitor© in this case. Note how the h-value varies, as the target plate alternately passes beneath the jet fingers and the spaces between them. Also note the discontinuity between the two zones. Averaged across the entire length of the oven, the overall heat transfer coefficient would be about 10 – 12 Btu/hr ft² F°, typical for ovens of this type, originally designed for baking pizzas in fast-service restaurants. Comparison values for a conventional oven would be 2 to 3 Btu/hr ft² F°.



3) *Product Results*

When foods are baked in impingement ovens, they are typically baked at about 20 - 25 °C lower temperature and for about 50 - 60% as long as in a conventional oven, though these values will vary tremendously depending upon the product characteristics. Another way to look at the comparisons is to calculate an 'energy input' value by multiplying the baking time by the average 'driving' temperature (difference between hot air and food). Then this number for impingent ovens can be compared with those for the same product baked in a conventional, natural convection, oven when the products are baked to similar temperatures and moisture contents. A series of tests was performed using a Jet Sweep© air impingement oven (Enersyst Development Center, Dallas, TX).

Over a range of 15 different products covering frozen pies to cake batters to bread dough to flakey pastry to cookies (sweet biscuits), the ratio of 'energy input' varied from 32.0 % (for a frozen fruit pie) to 74.5 % (for dense Raisin-Oatmeal cookies). The overall average for the 15 products was 50.8 %. Therefore, the impingement oven baked much faster at lower temperatures, potentially yielding substantial energy savings as well as saving on production time and floor space. These savings must be factored against the higher initial capital cost and maintenance on the air handling system.

An additional advantage to modern impingement ovens is that they can be automated, quickly changing from one product to another with no product loss at the time when one product stops and the other one starts, so there is almost no break in production. There is also less danger of 'flash heat' that will damage the first several rows of products when production starts up each shift. Instead of changing temperature, which can take a long time, the fan speeds can be easily varied, raising or lowering the h-value and hence the heat transfer rate, so products with different sizes and weights can be accommodated. Therefore, to the bakers trusted controls of baking time and oven temperature, we can add 'h', the heat transfer coefficient, to maintain desired product quality.

Hybrid Ovens

Microwave or Radio Frequency ovens (a special type of non-thermal radiant energy) potentially have certain advantages in terms of baking speed because they tend to heat the inside directly, not relying upon heat being transferred from the outside through the crumb. Unfortunately, bread and cakes will not brown or develop baked flavors in a microwave oven and they tend to heat unevenly. Cake interiors frequently get hard 'bones' in them and bread can turn tough & rubbery. Microwave generation is also inefficient, with as much as 40 % – 50 % of the electrical energy wasted as heat in the magnetron tube. It is unfortunate that the term 'oven' was ever applied to microwave heating appliances in the first place, for they are not ovens in the usual sense of the word. They actually are 'cooking the food in its own juices', heating the water, protein, etc. molecules directly by exciting their molecular bonds, especially the oxygen to hydrogen and carbon bonds.

Impingement baking also has certain advantages. It is faster than conventional baking (typically taking around half as long), even faster for relatively thin products, and produces good flavor and surface browning. It is limited by the internal thermal transfer characteristics of the foods, though. Thick products still take a long time for the heat to penetrate to the interior. Baking a refrigerated biscuit (scone) dough piece very rapidly can result in burning the outside while the inside is still cold and raw.

It is possible to combine two or more forms of heat transfer into one unit. By contributing about 40 % of the energy needed to bake the food from microwaves and the rest from impinging hot air, the time can be cut in half again, to one fourth the times required by a conventional oven.

For example, several foods were baked in a conventional oven (C), an impingement oven (I), and a hybrid oven (H). (These data are relative, and may apply only to the specific ovens tested.)

Baking Time, min

Product	C	I	H
Muffin	12	7	3.5
Hard Roll	20	10	5
Frozen Pie	60	27	15
Frozen Pizza	10	4.5	2.5
Cookie	12	4	2

Again, results will vary with product, oven model, and other considerations, but it is obvious that the production time can be substantially reduced. Unfortunately, there are still limits to accelerating production. Product characteristics begin to suffer if pushed beyond these limits. As mentioned, impingement can burn the outside and microwaves can change the internal texture. Microwaves also tend to drive the moisture from the interior to the exterior more rapidly, so hybrid ovens will dry the product out more rapidly, resulting in yield loss and reduced shelf-life, unless the process is carefully designed.

Some formula adjustments may be necessary. In the case of cakes, for example, batter water content and emulsifier systems may need adjusting. These are commonly used by bakers to control their products anyway. Another problem though is that slower-release leavening acids may not react to release the CO_2 until after the top crust has been set by the impingement. The result can be a lower volume and a hard 'ring', separated by cracks around the top. When the leavening does release, the top cannot rise uniformly so it cracks on the top, generating a muffin-shape, like a volcano, with a steep rise in the center but no lift along the edges. Replacing the normal double-acting baking powder by using Cream-of-Tartar or Mono-Calcium-Phosphate with Sodium Bicarbonate as the CO_2 source will partially compensate for that problem.

Humidity in Baking

We have discussed how time and temperature have been used since time immemorial to characterize & to control the baking process. We now realize that the efficiency of heat transfer can also greatly affect how rapidly and in what manner something bakes. Even though two ovens may be set for the identical time and temperature, their baking rates can still be drastically different. Now let's finish our discussion with another factor that has been known to affect baking, but has been difficult to measure and hence difficult to accurately control.

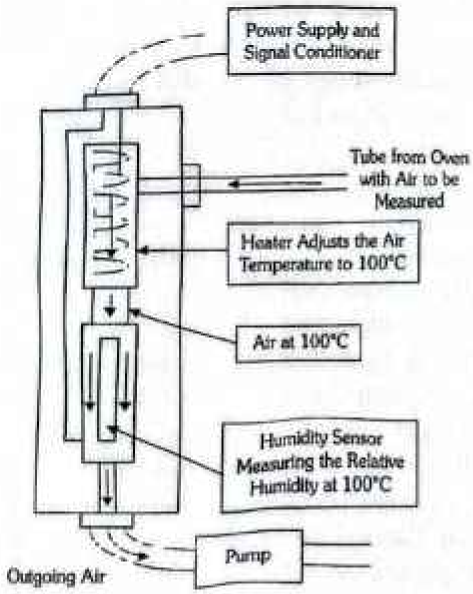
A) *Traditional Controls*

An experienced baker sticks his arm into an oven and declares "The oven is hot today" or "The oven is cold today". If the thermometer reads the same temperature on both days, how can the oven be 'hot' or 'cold'? The answer to this question is humidity. If the night shift operator closed the stack dampers to save gas, and the day shift did not reopen them, the oven filled with steam. The steam condensed on the baker's arm when he put it inside the chamber, giving up its latent heat of vaporization and burning him. Contrary-wise, if the damper had been left wide open, the air inside the oven would be drier. Even at the same temperature, the lack of steam would make his arm feel less hot because moisture evaporated from (instead of condensing on) his skin, keeping his arm cooler than the air temperature. Oven humidity affects baking, such as affecting crispy crust development on hearth breads. It also affects moisture loss, cake color, and cookie spread, for example.

B) *How to Measure Humidity*

Humidity was commonly measured by the classical wet/dry bulb thermometer pairs. The procedure is quite accurate and reproducible at moderate temperatures but is relatively slow and requires a supply of liquid water to continuously moisten the wick. The 'hair' hygrometer requires a fiber that can absorb or lose moisture, changing its length as it does so. Early electronic instruments used two noble metal grids separated by a porous plastic membrane saturated with a hygroscopic salt. The amount of humidity in the air affected the amount of salt dissolved, and hence its electrical conductivity. Many other methods have also been developed, but they do not work well at elevated temperatures, especially much above 100 °C, or they are very slow and impractical for routine control purposes.

More recently, some engineers have taken a different approach. They continuously withdraw a sample of oven air, condition it to 100 °C, and pass it through an instrument to measure the humidity of the conditioned air with a rapid response sensor. We acquired such an instrument (in this case, manufactured by BRI-Australia) and used it to measure the actual humidity in an oven at the same time various products were being baked. Our unit was designed for static mounting on or near the external oven frame, but the original developers have also developed a self-contained model which can travel through the oven with baking product, in much the same manner that the h-Monitor© can measure heat transfer rate.



C) *Effects of Humidity*

Several typical products were then baked in three different ovens. Two were gas heated food-service convection ovens, one direct fired and the other indirect fired. The other oven was an electrically heated impingement unit (the same one used for the h-value tests reported above). Humidity levels were changed 'naturally' by including 'dummy loads', pans filled with water-saturated Perlite (a porous expanded mineral), both preceding &

following the test samples, simulating a full oven. Cakes, cookies, and small bread loaves were baked under various combinations of time, temperature, airflow rate, and humidity and their properties were measured.

As an example, cakes baked under various humidity conditions in direct and indirect heated gas ovens at two different fan speeds showed higher moisture loss rates and greater firmness at lower absolute humidity (about 15 g H_2O/Kg dry air) than at higher humidity (about 26 g/Kg).

Their crust colors were lighter, volumes were higher, and crumb was tendered at higher oven humidity levels, though baked at the same time and same temperature, the baking losses were lower as well, but there was some surface stickiness apparent on the high-ratio white layer cakes.

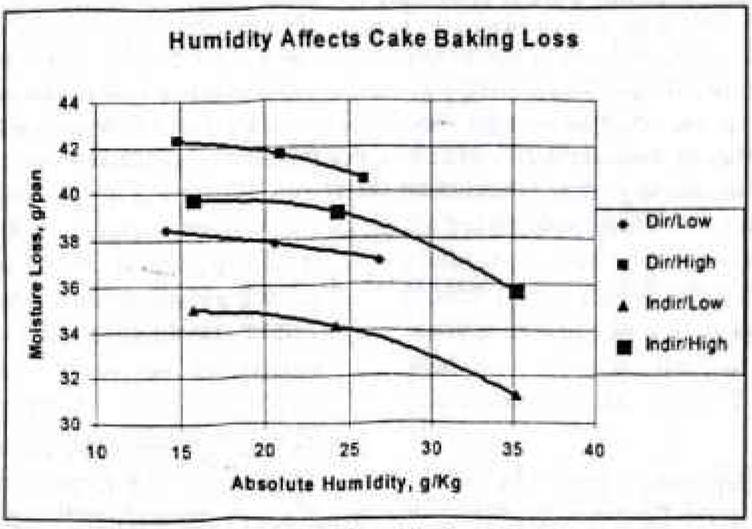


Figure 4 The evolution of humidity in cake baking process

Conclusion

To the traditional controls of time and temperature, the baker now has available heat transfer coefficient and oven humidity that can be accurately measured and hence controlled in real time. The result should be an improvement in a bakery's economics and in product uniformity and quality.

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