Interaction of Water Activity and Drying Curves

In this column I will discuss an aspect of engineering and design that I don't believe I've ever mentioned before. The discussion comes after recently encountering a common oversight that I've run across a number of times in the past.

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The collection of water activity (A_w) or equilibrium relative humidity (ERH) information is a very common practice in the food industry. Most often these tests are performed to evaluate and ensure the microbiological and chemical stability of foods. This is accomplished using a number of techniques. Because discussions of the techniques and importance of measuring water activity can be found in a number of texts, e.g., *Moisture Sorption: Practical Aspects of Isotherm Measurement and Use* (1), I will not go into the details of the measurements and their interpretation here. Instead, I will discuss the importance and use of these measurements for understanding drying operations, which include not only simple drying, but also operations such as baking and frying.

The transfer of water from products to the environment is controlled, to a great degree, by the apparent diffusion of water vapor to, or from, the environment to the product. In the case of drying, baking, or frying, the transfer is from the product to the environment. In the case of staling of products such as cereals or snacks, the transfer is from the environment to the product. In either case, the transfer of moisture may be approximately described by a first-order transfer process:

$$(M - M_{eq}/M_0 - M_{eq}) = \exp(-kt)$$

where M = moisture (db) at any time
M_{eq} = equilibrium moisture (db)
M_0 = initial moisture (db)
k = rate constant
t = time since beginning the process

The rate constant (k) is a strong function of the thickness of the object and the apparent diffusivity of moisture in the object. Apparent diffusivity is a relatively weak function of temperature. The question is, if diffusivity is a relatively weak function of temperature, why is it that increasing temperature can have a substantial effect on the rate of drying?

Temperature can have a substantial effect because of its effect on equilibrium moisture (M_{eq}). This effect comes from two sources. First, bringing air from a room into the drying and heating cycles results in a substantial change in relative humidity (RH). This effect can be observed using a psychometric chart. For example, taking room-temperature air at 80°F and 50% RH and heating it to 150°F will result in a decrease of the RH to approximately 6%. Because the moisture in equilibrium with the humidity is much lower at 6% RH than at 50% RH, the driving force for drying increases, and according to the equation given above, the rate of drying increases.

The second temperature effect is often overlooked. Generally the water activity (ERH) curve for a product is generated at or near room temperature. This is appropriate if one is interested in measuring the microbiological or chemical stability of the product during storage. This is not appropriate, however, if one is interested in measuring product drying, etc., at higher temperatures. Water activity (A_w) is a relatively weak function of temperature but generally increases with temperature. This would lead one to conclude that equilibrium moisture (M_{eq}) is not a strong function of temperature, which is erroneous. Because of the shape of the water activity (ERH) curve, changing the temperature can have a substantial effect on the relative value of M_{eq}, particularly at low humidities. I recently encountered this situation while working with a product. At room temperature (70°F) and approximately 10% RH, M_{eq} was approximately 3.5% (db). At the same RH but at 150°F, M_{eq} was only approximately 1.5% (db).

Let's consider what this means. At room temperature, the time required to dry to 3.5% moisture (db), would be infinitely long. This occurs because the numerator on the left side of the equation given above becomes 0. Time would not be infinite if the product is dried at 150°F, because the numerator on the left side of the equation is finite. This is an very artificial example, however. Consider a case in which a product is dried from 40% moisture (db) to 4% moisture (db) at room temperature. If an experiment is run, we find that it takes 3 hr to accomplish this task. However, at 150°F, M_{eq} would be 1.5%, and assuming that k does not vary with temperature, the required drying time would only be approximately 1.9 hr.

The difference between the required time at room temperature and at 150°F grows as the target moisture gets closer to the room temperature M_{eq}. For example, using the same data from the room temperature experiment, if the material is to be dried to 3.6% moisture (db), the calculated time required at room temperature would be more than 4 hr, whereas at 150°F the time required would be only approximately 2 hr.

It's obvious from these calculations that to accurately predict the performance of a drying process at temperatures other than room temperature, one must develop the water activity (ERH) curves at elevated temperatures. Unfortunately, it's been my experience that this seldom is done, and it's difficult, if not impossible, to do at temperatures substantially above room temperature.

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There is another reason for determining A_w at the temperature of interest. Suppose one knows that the moisture at the drying temperature of interest is 1.5%, but when the drying test is performed the drying rate approaches 0, i.e., the moisture does not appreciably change once the material is dried to approximately 3% moisture (db). This result indicates the product is "case-hardened." This is usually the result of the formation of a glassy or leathery region within the dried piece, i.e., a moisture and temperature combination has been created within the piece that is close to, or below, the glass transition temperature of the material being dried. As the glass transition temperature is approached, the diffusivity of the moisture approaches 0, so the rate of drying approaches 0. This usually indicates that the drying conditions are too severe, which often results in the formation of stress cracking in the finished product immediately, upon removal from the drier, or some time after the material has been removed from the dryer.

It's been some time since I asked this, but I'm again asking readers for ideas about subjects that they'd like me to cover in this column. It is sometimes difficult to come up with new subjects that would be of broad interest and are not too complicated to explain in a short column or series of columns.

Reference

1. Bell, L. N., and Labuza, T. P. *Moisture Sorption: Practical Aspects of Isotherm Measurement and Use*. AACC International, St. Paul, MN, 2000.