HOW DO WE KNOW when coffee has finished roasting? One might think coffee is considered roasted when the final target temperature is reached. If a final temperature of 205 degrees C (400 degrees F) is specified as an endpoint, and the coffee reaches this temperature, it’s roasted, right? In his book *The Coffee Roasters Companion*, author Scott Rao argues that this is not necessarily true.

Introducing the concept of baked coffee, which he describes as “flat” and “dull,” Rao writes, “Intentionally extending the last few minutes of roast usually creates baked flavors and should be avoided. Should a roast stall, meaning the bean temperature stops rising (i.e., the rate of rise [GOR] is 0 or has a negative value), baked flavors will dominate and sweetness will all but disappear.”

**BAKED BEANS**

Observations on Water Content During Coffee Roasting

BY JAMES DAVISON

Photos by Peter Davison, Ikigai Camera
The "missile switch" at the top left corner of the roaster’s primary control panel disables the panel so the roaster can be controlled through a computer.

As a refresher, ROR refers to the change in roast temperature over time (rising 5 degrees over 30 seconds, for example). Most coffee roasters not only monitor the roaster’s temperature, but the rate of change of that temperature inside the drum. Rao asserts that when the rate of change approaches zero, the coffee tends to pick up the taste attributes commonly referred to as baked. Thus, two identical coffees roasted to the same end temperature can taste drastically different, depending on how they were roasted.

Measuring Water Content During Roasting

There are some major differences in the composition of green coffee versus roasted coffee. One big difference is the greater mass of a green bean compared with that of a roasted bean, caused by water leaving the green bean during roasting.

Using the example of a light roast with a 10-kilogram (22-pound) batch size, about 12.5 percent mass will be lost as water, resulting in a total decrease in weight of 1.25 kilograms (2.76 pounds). Water will account for 1 kilogram (2.2 pounds) of the mass lost. (The remaining mass loss likely can be accounted for by CO2 and other volatiles.) While there may be other factors that affect this number—such as the green coffee’s water content, the roaster, the environment and desired roast (a darker roast will tend to lose more water than a lighter roast)—these figures should serve as reasonable starting points for this discussion.

If this water could be measured during the roast, the measurement could be used to predict the final mass of the coffee. This would involve measuring the properties of the exhaust gas leaving the roaster.

Air is a mixture of several gases, mostly nitrogen, oxygen and water, with trace amounts of argon, helium and hydrogen. The amount of water in air is described as the air’s humidity. Air will be able to absorb more or less water depending on its temperature and pressure. Hot air, like that inside a coffee roaster, can evaporate liquid water into gaseous water. There is a more complicated explanation for this phenomenon, but for simplicity’s sake, consider that hotter air has a greater capacity to hold more water than cooler air. One way to measure the amount of water in the air—as detailed in an article published in the Journal of Food Engineering in 2001 titled, “A preliminary study on the feasibility of using composition of coffee roasting exhaust gas for the determination of the degree of roast”—is to collect the air from the roaster and cool it until it returns to a liquid state. To collect all the air coming out of a coffee roaster and cool it is difficult, energy intensive and time consuming. Another way to do this is to measure the capacitance of the air.

Capacitance is a measurement of how much electrical charge a substance can hold, and can be used to infer other properties, such as density. Water has high capacitance, and air with higher humidity can hold more electrical charge. This ability to hold charge can be measured by a capacitive-relative humidity probe, which can be placed in the coffee roaster’s chimney. This sensor provides a number that reflects the ratio of the amount of water in the air compared to the theoretical maximum the air could hold. The theoretical maximum can be calculated using experimental data that is relatively simple to collect. (We used formulas from The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use. A free calculator is available at aqua-calc.com/calculate/humidity.) This equation can then show the amount of water in the air volume being measured, if the ratio is known and the theoretical maximum is calculated.

The result of these equations gives the amount of water in the air at any given point during the roast. The total amount of water that has left the roaster will be the sum of all measurements taken during the roast. At the end of the roast, the result will be the total amount of water multiplied by the volume of air that went through the machine. If this number is divided by the amount of air that went through the machine, or the airflow rate, the total mass of water that came out of the coffee will be all that is left. The result is a method of predicting the final mass of the coffee by subtracting the measured value from the coffee’s initial mass.

We hypothesized that the amount of water leaving the coffee (by mass) could be calculated by measuring the relative humidity of
the exhaust gases. We attempted to test this theory using the method detailed in the
following pages.

Observations

To conduct our observations, we used an electrically powered, 1-kilogram coffee
roaster from the Chinese company North Coffee (now distributed by Mill City
Roasters). Two sensors were installed in the coffee roaster’s chimney. These sensors
were installed high in the chimney, approximately 5 meters (16 feet) up, because
the exhaust gases from the roaster must cool somewhat to be within the sensors’
measurable temperature range.

A sensor made by Novus (model number RHT-DME) was used to measure the
exhaust air temperature and relative humidity. This sensor does not measure
temperature using type K thermocouples, the kind found in most commercial
roasters. Rather, it uses a device called a thermistor, which is housed in the same
probe as the relative humidity sensor.

A custom-made anemometer, which functions like a windmill, was used to
measure the airspeed in the duct. (Most commercial models were too expensive
and/or did not provide the measurement range we needed, so we designed and
3D-printed our own, using ABS plastic that would withstand the high temperature.)

A small motor was attached to the blades of the fan. When the fan turned because
of air flowing past it, the motor would generate a small voltage. This voltage could
be amplified, filtered and read by the roast controller to gain a value for the
airspeed. It was calibrated using an industrial anemometer while the roaster was
cold. The industrial anemometer was removed from the circuit and the signal
reported by the 3D-printed anemometer was correlated to the speed reported by
the industrial anemometer.

We did not measure the initial moisture content of the green coffee used as
the devices required to measure that data were cost-prohibitive.

On the day the tests were performed, the ambient conditions were:

- Temperature: 17.8 degrees C (64.04 degrees F)
- Relative humidity (RH): 75 percent
- Water content was calculated as 11.4 g/m³ (grams of moisture per cubic meter
  of air, or “absolute humidity”)

In the first test, the machine was left to idle with nothing in it, with the heater on
just over half and the airflow turned down to just below half. The temperature
of the roaster was left to approach stable (equilibrium) conditions, meaning it
was neither heating up, nor cooling down. The humidity observed in the stack
could therefore be related only to the humidity already present in the air. The
critical thing to note for this test is that the concentration of water in the air
outside the roaster should be identical to the concentration inside the stack. The
temperature and relative humidity will change, but the concentration will be the
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same. However, there may be slight variation due to some variation in the measurements made by sensors inside and outside of the duct, and also due to error between the sensors.

At equilibrium, the stack temperature was observed as:
- Temperature: 74 degrees C (165 degrees F)
- Relative humidity: 5.3 percent
- Water content was calculated as 0.8 g/m³

The overall concentration calculated inside of the duct was 0.8 g/m³ different from the background humidity on the day of the test. This variation was considered negligible, so we proceeded with the second test.

The second test (Figure 1, left) involved placing a known mass of water—275 grams—inside the roaster into a stainless-steel tray beneath the elements, at the conditions established in Test 1. The internal temperature of the roaster was stable at 231 degrees C (447.8 degrees F) and the temperature inside the exhaust stack was 75 degrees C (167 degrees F). The water was placed underneath the elements inside the roaster and left to evaporate. As the water began evaporating, the relative humidity climbed until it hit a peak value of 17.5 percent. Water was observed steadily leaving the roaster until most of it had evaporated from the tray within the roaster. At this point, the humidity declined back to the background levels observed in Test 1. The total amount of water leaving the machine was calculated at 268 grams. This was approximately equal to that of the water that had been placed inside the roaster.

Figure 2 (right) shows the period of time after the water had been added. The total amount of water is shown in green. This line shows the amount of water that was introduced at the start of the test (275 grams). As the water evaporates, this amount decreases, until there is no more water left inside the roaster. The gradient or slope of this line shows the drying rate.

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In the third test (Figure 3, right), 1,029 grams of Sumatran coffee was placed inside the roaster. The roast took just over 12 minutes. During the roast, the minimum airflow was 0.84 m³ per minute, the average airflow was 0.85 m³ per minute, and the maximum airflow was 0.90 m³ per minute. The total amount of air that went through the roaster was 11.6 m³. The humidity observed in the exhaust duct steadily climbed as the coffee heated up. The amount of water leaving the roaster steadily increased throughout the roast until just before first crack. The water leaving the roaster then sharply increased through first crack, before declining just before the coffee was dumped out of the drum for cooling. The final mass of the water leaving the drum was calculated at 157.9 grams, using the same method as the previous tests. The mass difference measured when the coffee was weighed was 158.7 grams (i.e., the roasted coffee weighed 158.7 grams less than the green coffee placed in the roaster).

Figure 4 (below) shows the drying rate throughout the roast. It’s particularly interesting to note that drying took place throughout the entire process. The rate at which the coffee was drying (shown by the slope of the purple line) was lowest at the beginning of the roast, progressed gradually throughout the roast, then sharply increased at the end of the roast. That is to say that, post first crack, water was observed leaving the coffee rapidly.

Water Transformation During Roasting

In chemical engineering, a unit operation is a building block used to design a process. Processes can be modeled based on the type of unit operation they involve. One specific operation that concerns coffee roasting is drying—or removing water from a solid. The rate of drying is a function of airspeed and air temperature. Conductive, convective and radiant heat transfer all play a role, to varying degrees, in drying. Variables such as drum speed and airflow can be used to change the characteristics of a drying operation. Simply put, drying is a function of how hot a substance gets and how much air is available to draw in water.

Remember that the hotter the air, the more water it can absorb. Some of the water leaving a substance during drying transfers into the hot air stream. The amount of hot air available is related to the flow rate of air across the substance. In the case of a coffee roaster, air is drawn into the air intake, heated by either elements or burners, passed through the beans, and finally exhausted out of the roaster. To affect the rate of drying, the operator can increase the amount of energy by supplying more heat to the drum, or by raising or lowering the airflow rate. Beans that are left at high temperatures with high airflow rates will experience more drying than those with lower
temperatures and airflow rates. But this affects coffee only to a point.

Espresso Coffee: The Science of Quality, edited by Andrea Illy and Kimantoni Viani, provides a simulation of heat transfer through a coffee bean. Heat transfer is a measure of how heat is conducted inside the bean. To understand how heat is conducted into the bean throughout the roast, the latent heat of vaporization must be considered.

Latent energy is defined as the amount of energy required for a substance to undergo a phase transition—transforming from a solid, liquid or gas into another state. In the case of coffee, the most important phase transition is the transformation of liquid water to gaseous water, or steam. This transition does not occur simply because a significant amount of energy is required to raise the temperature of the coffee when it’s at room temperature and has high water content. A larger amount of coffee generally will need a higher starting temperature in the drum. Failing to supply adequate energy at the beginning of the roast will result in a longer roast time. However, while the temperature has to be high enough to bring the roast up to a desirable temperature quickly, it can’t be so hot that the outside of the bean will burn on contact.

After the beans are charged into the coffee roaster, there will be a sharp increase in the temperature of the coffee. As the coffee comes up to temperature, there must be enough time for the heat to transfer evenly in the bean. Further along in the roast, the latent heat is conducted into the bean. To understand how heat is conducted into the bean throughout the roast, the latent heat of vaporization must be considered.

For a coffee roaster, this sets up the following scenario: The drum of the coffee when it’s at room temperature and has high water content. A larger amount of coffee generally will need a higher starting temperature in the drum. Failing to supply adequate energy at the beginning of the roast will result in a longer roast time. However, while the temperature has to be high enough to bring the roast up to a desirable temperature quickly, it can’t be so hot that the outside of the bean will burn on contact.

Applications in Roasting

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Studying the water that leaves the roaster during the roasting process—if performed in conjunction with sensory evaluations—might provide an explanation for how “baking” occurs. There is also a physical explanation for what has long been observed by coffee roasters. First crack is known to be a critical phase in the roasting process. It is where temperatures, smells and colors are closely monitored to ensure good product. At the drying rates observed in these tests, there can be a large difference in the final weight of the product with only small differences in the time after first crack.

Temperature can be used to set the final end point for a certain degree of roast. A lighter roast will have a lower end temperature, a darker roast a higher end temperature. But temperature alone does not answer the question, “When is a coffee considered roasted?” If there is indeed a physical number that can be assigned to a roast when it is done, it can be measured. If it can be measured, it may mean an automatic system will be able to determine the best point to end a roast. It could also be used to ensure a coffee is not roasted beyond the point where it will achieve its optimal flavor profile.

Perhaps what is referred to by some as “baked” coffee is actually just a roast that has dried too long. The tests detailed in this article outline one possibility related to the cause of “baked coffee.” The next step in this exploration would be to add sensory analysis along with moisture-loss measurements. Tools to measure moisture content, density and color of the beans would also add depth to this inquiry.

The water content of coffee may be an important physical trait that can tell a roaster when a coffee has finished roasting—if it can be measured reliably. It could also be an important indicator of how a roast is progressing, and can help to explain the heat balance inside a coffee roaster. This will help to ensure more consistent, better tasting coffee and, I believe, help roasters avoid “baked” coffee.

JAMES DAVISON is a chemical engineer from Melbourne, Australia, with a passion for exceptional coffee. He is the owner and founder of Williamstown Roasters. Davison won two silver medals and one bronze at the Australian International Coffee Awards. He developed his own specialty roasting software that logs information from the roaster and controls the process. Davison has worked in the food manufacturing industry making chocolate, in the hydrocarbon industry, and as an engineering consultant and designer. He now combines his knowledge of and experience in engineering with his passion for coffee. He takes a precise, scientific approach with meticulous care in search of the best possible coffee.