Online Thermal Analysis of Batch Roasted Coffee Beans

Cameron Kelly, Jonathan Scott

***Abstract*—We constructed and instrumented a fluidised-bed coffee roaster. This work has been carried out as part of a search for the "ideal point", which is the point in time when an expert roaster would terminate the roast in order to yield beans that produce the optimal brew. We roasted Costa Rican Arabica beans whilst controlling the roasting temperature to follow a linear ramp. We measured and recorded the input, output, and coffee bean surface temperatures. We introduce the idea of "bean load", an uncalibrated measure of the heat load presented by the material being roasted. The bean load under constantly-ramping bean surface temperature shows the roast is increasingly endothermic. Toward the end of the roast the endothermic phenomena decrease, or are assisted by exothermic activity. The bean load also has a repeatable dip around first crack. Due to limitations with the roaster we were not able to make reliable measurements at and beyond second crack. We observed no waypoints or events that might be used to pinpoint the "ideal point" to end the roast.**

Keywords*—*Coffee Roasting, Temperature measurement, Fluid bed, Bean Load

I. Introduction

COFFEE roasting is an important step in the process of bringing coffee from green bean to cup. It is the roasting process that takes the green coffee and develops the flavours and aromas for which coffee is so valued. Roasting is, most importantly, the step that imparts the greatest added financial value. Roasting is an extremely complex process where the coffee undergoes many chemical and physical changes, not all of which are fully understood. [1, 2, 3, 4, 5] It is accepted that coffee tastes better the shorter the time period between roasting and consumption, and the shorter the time between grinding and brewing. Over the last decades of the 20^{th} century machines for grinding and brewing moved from factories to the home. In this century low-cost home-roasting machines appeared [6, 7], but they have not proliferated because roasting beans is something of an art, requiring an expert roaster. This need for expertise is much of the reason behind roasting remaining the step with the greatest addition of value.

It is our ultimate aim to automate the roasting process, so that it moves effectively from a commercial to a domestic situation.

A. The roast process

Coffee roasting is the process of applying heat to green coffee in order to produce roasted coffee. During the process the coffee undergoes changes, of which the most noteable are colour, size, and density. [1, 2, 3] The expertise of a roaster lies in interpreting the evidence of changes in bean colour, bean size and texture, roast chamber temperature, the smell of the beans[1], and elapsed time, to determine an ideal point at which to terminate the roasting process to produce beans that will lead to the most desirable brew. This "ideal point" at which to quench a roast is typically thought to be an interval of 10–15 seconds in an 8–15 minute process.

The changes that happen to the beans occur in distinct phases. The phases are often separated by notable events. Most sources in the literature consider the first phase to be spent driving the major part of the moisture from the beans, which typically start with 8–15% water content. Mailliard reactions also start in this phase, turning the beans first yellow and then brown. This phase is ended by the most notable event, "first crack". First crack is where the beans "pop" much like the popping of popcorn. This is the rapid expansion of the bean caused by buildup of moisture and other volatiles in the core of the bean. [1, 2] It results in the bean density falling significantly.

In the second phase, starting after first crack, pyrolytic reactions start. The beans turn fully brown and sugars start to caramelize. A second crack is caused by the build up of gaseous output products from the pyrolytic reactions. These reactions cause the breakdown of the cell walls and oils start to seep out of the bean. Second crack can be violent enough to blow off chunks from the beans. The colour at this stage is a very dark brown. Continuing on, the bean blackens and more oils are released. The roast is ended when the desired degree of roast in reached, typically shortly before second crack commences.

This complex process of coffee roasting has been given a great deal of thought over the years. Nevertheless, little of the literature comprises quality assured sources. Vastly more of the literature is found on the web and in popular publications. The first scientific collated work on coffee processing including roasting was written in 1987. [2] Very little quality-assured literature exists prior to 2000.

The "Sweet Maria" web site, [8], has a substantial library of articles and extensive tutorials based on good science, and is perhaps the "go to" site for coffee roasting information, much as Frank Shellock's http://www.mrisafety.com/ is the major source for information on safety of medical implants in MRI scanners.

Some authors have looked at determining state of roast by looking at the roaster exahust gas composition. [9, 10, 11]

[1]Expert roasters may have to do without access to the exhaust from the roaster. In industrial situations the exhaust is expelled away from the equipment for health and safety reasons. Provision is usually made for small quantities of beans to be pulled momentarily from the roast chamber for the operator to observe and sniff.

Mass spectrometry should be able to identify compounds in the exhaust gas that could portray the progress of the roast and identify the ideal point to quench the beans, but normally it cannot operate in real time. In [9] gas chromatography was tried. In [10, 11] real-time laser ionisation mass spectrometry was investigated. None of these works has lead to a commercial product, either because of cost or reliability.

A more common technique is to look at colour of the coffee. [12, 13] The concensus is that colour is not repeatable enough to indicate the state of the roast. [14]

There is a considerable literature on the chemical makeup of green and roasted coffee, see for example [15, 16]. There are techniques for analysing roasted and brewed coffee to help in identifying what makes coffee good. [17, 18, 19] Nevertheless, this does not provide any insight into how one might identify the ideal point in real time.

Roasting is made more complex because the method chosen to roast coffee can effect the resulting coffee [20, 14]. This includes the method of heat transfer [21], the temperature profile used in heating the coffee[22], and the method used to cool the coffee after roast [23]. The intricate nature of coffee roasting means that controlling and predicting end of roast is not straight forward.

B. Temperatures affect on roasting

Temperature measurement is often used in roaster control as it is straight forward to measure and report. The exact temperature that is measured is dependent on the roaster and where the temperature sensors are located. Meaning that a temperature result in not necessarily transferable from roaster to roaster.

It is well accepted roast temperature does affect the final roast. [1] Moreover the temperature profile of a coffee roast can effect the quality of the coffee produced. [24] The coffee temperature has been suggested as an indicator of degree of roast. [25] Most of the literature uses “step” temperature profile that has the roasting environment at a fixed target temperature. The “step” profile simulates the temperature profile that coffee would experience in a drum roaster -a common comerical roaster.

We use a fluidised bed roaster in which we can precisely control the bean temperature (Details in the next section). This means we can use a different temperature profile then the standard step. We use a PID-fixed linear ramp -unusual in literature. The “Ramp” profile should give us a sensitive view of the coffee’s thermal effect on the environment. The hope is that by watching the temperatures we will be able to track the coffee’s progression through the roast.

II. Method and Equipment

For this experiment we built a small scale fluidised-bed coffee roaster. A fluidised-bed roaster roasts coffee by blowing hot air though the coffee. The air flow causes the beans to move and flow as if they were in a fluid.[1] The mechanical section of our roaster (figure 1) consists of a blower piped into a heating element. The hot air is then ducted in the base of a glass roasting chamber (figure 2). Suitable thermal cladding normally encloses the hot parts to minimise heat loss.

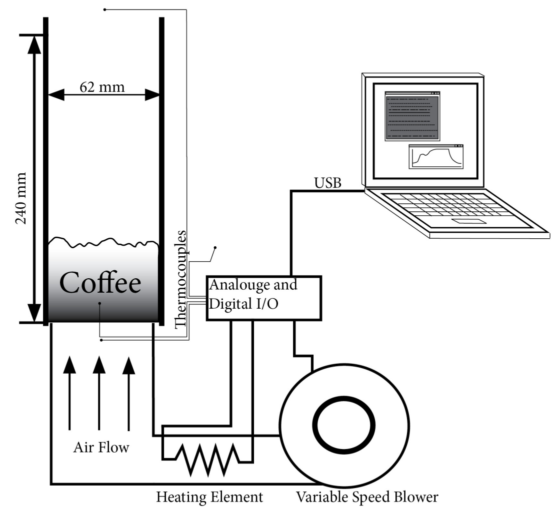

Fig. 1. Block diagram of the fluidised-bed roast chamber and attached equipment

A. Temperature and control

We use four k-type thermocouples to measure and control the roast temperature. The first thermocouple measures the pre-roasting chamber temperature. The second thremocouple is situated inside the roasting chamber, in close communication with the beans in the bed, and measures the bean surface temperature. The third measures the exhaust temperature at the top of the glass chamber. The final thermocouple measures the ambient temperature. All four thermocouples are connected to thermocouple amplifiers. The output of the amplifiers is fed into a LabJack measurement interface [26].

A computer receives the temperature data from the LabJack. The computer then sets the target temperature, calculates then next control value, and logs the temperature readings. Temperature measurements are taken every $250ms$. A PID control method is used to calculate control output value. The desired output value is sent to the LabJack which controls a heating element by means of a PWM signal via a solid state relay. The coffee thermocouple is used for the temperature control to ensure the coffee stays at target temperature.

The target temperature is set to ramp starting from ambient temperature. The ramp ends when a predefined target temperature is reached. In our experiments here, the ramp was set to $0.28°C/s$ with a target temperature of $230°C$. The target temperature was chosen to be near the limit of the roaster, after which control becomes unreliable because the heater reached 100% power.[2] The ramp rate was chosen so that the roast would reach completion in what is considered an acceptable

[2]The controller also has the capacity to adjust fan speed. Higher temperatures can be achieved once the heater reaches full power by reducing fan speed. We have not availed ouselves of this facility as we did not want to get into problems with the fluidisation of the bed.

Fig. 2. The glass roasting chamber

length of time for a commercial roast, between 10 and 15 minutes.

We hope that variations in the temperatures reflect the relative endothermic or exothermic nature of the coffee.

At this point we introduce the idea of "bean load". We are interested in looking at the amount of energy absorbed or emitted by the beans in the roaster during the process. The bean load is calculated as the difference of input temperature to output temperature normalised to an empty run:

$$L_{\text{bean}} = \frac{(T_{\text{in}} - T_{\text{out}})}{F} - \frac{(T_{0_{\text{in}}} - T_{0_{\text{out}}})}{F_0} \quad (1)$$

where F is the air flow rate, T_{in} is the air temperature just prior to the bean chamber, T_{out} is the air temperature just at the exit of the bean chamber, and F_0, $T_{0_{\text{in}}}$ and $T_{0_{\text{out}}}$ are the same for the case of an empty roast chamber. In effect, L_{bean} represents the energy absorbed by the beans (the load in the roast chamber). For the case of a constant ramp in chamber temperature, and an inert load (such as glass or ceramic beads) the bean load will be a constant, as the heat capacity of an inert load remains constant.

III. Results

Figure 3 shows the temperature of the coffee as it follows the temperature ramp. The coffee was heated from room temperature to 230 degrees Celsius. A load of 135g of Costa Rican coffee was used for the test. At the end of the cycle the beans were over-roasted, so that the "ideal point" is guaranteed to be in the plot, but the exact position is unknown. The bean surface temperature adheres to the target (ramp) temperature with little variation for the entire duration of the roast. The plot also contains the input and output air temperatures, the input temperature being the higher temperature, of course.

The interesting part of figure 3 is the bean load. The data in the bean load traces has been smoothed by a median filter to remove noise spikes. The median filter has a window of 50 points, and the sample rate is 4 Hz. In the very early stages of the roast (up until 100 s) bean load increases rapidly. Bean load then increases more linearly until around 550s. Between 550 and 600s there is a slight increase above linear giving a barely-discernable bulge. Above 600s the trace then levels out. There is a narrow dip that appears to align with the occurrence of first crack at around $700s$. After the temperature ramp levels off when the roast reaches $230°C$ there will be a sharp transition. An inert load will slew from a constant heat input to zero heat input. We are not able to make any statements about the case with beans, as it will not be possible to separate the transition from background changes, making the bean load an unreliable indicator around this event.

These characteristic aspects have been observed on multiple roasts, and have been seen by other researchers running similar equipment. Only one data set is displayed here for reasons of clarity.

We have assumed that the flow rate, F, remains constant throughout these experiments. This may not be strictly true, as it is the fan drive that remains constant, and the density of the beans does change throughout the roast cycle. Nevertheless, our fluidised-bed roaster includes a considerable amount of baffling (to mix air after the heater) and other flow resistance, and we consider the assumption to be safe.

IV. Analysis

In order to gain confidence in our measure of "bean load" we first tested an inert load of glass marbles. We used the same roast conditions as the coffee. Since the inert load has a fixed heat capacity for all temperatures reached in the roast we expect that our measure of bean load should not change. Referring to the trace in figure 3, this is what we see. After the initial ramp the bean-load trace for the inert load remains essentially constant, varying less than plus and minus a quarter of a unit. When the temperature levels off, it slews downwards. It appears that this inert-load bean-load drops below zero for the constant-temperature case, and we attribute this to the zero correction which has been carried out without any material in the chamber, and therefore has a slightly higher flow rate. In other words, the zero calibration is inexact, but we are not concerned with this.

In the early part of the cycle (below 100 seconds), the roaster is heating the chamber and stabilising. We attribute the near-linear ramp from 100 to 500 seconds mostly to evaporation, but

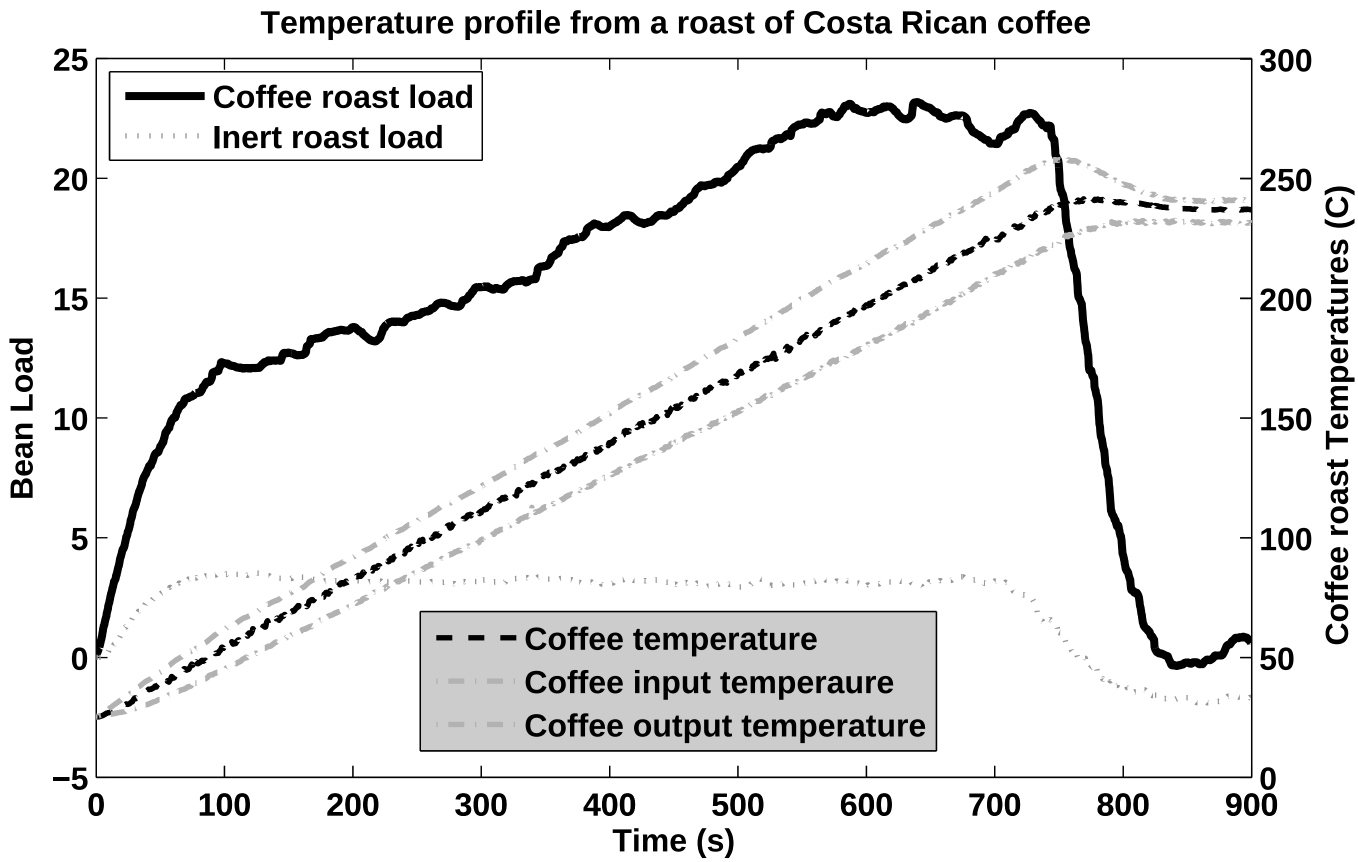

Fig. 3. Plot of input, output and bean surface temperatures and "bean load" during a coffee roast, and "bean load" in the case of an inert load substituted for the beans.

increasingly to pyrolytic reactions that are also manifested in the changes in bean colour. In other words, heat is used to boil off water and break down organic molecules. This is strongly endothermic activity, and it is increasingly endothermic as time goes on.

Just after 550 seconds there is a small upward bulge, implying that more energy is being used to break down the organic material. Then around 600 seconds the trace levels out. This suggests that either the reactions consuming energy reduce, or possibly they are joined by some exothermic reactions. Exothermic activity close to the end of roast is occasionally reported in the popular literature. Although we have never observed a net exothermic condition during a roast, we suspect that some exothermic reactions do start prior to first crack. It is obvious that the reactions will eventually become very exothermic at the point where the beans catch fire.

First crack onsets at 700 seconds and lasts 15–20 seconds. It is associated with a brief dip in bean load, followed by a small peak. We suspect that the dip and peak, which is repeatable from roast to roast, is a consequence of the change in bean density, turbulence in the chamber, and the impact of this on air flow moment by moment.

V. Conclusion

We have introduced the interesting idea of "bean load" and used it to examine the process of roasting coffee beans. Like a number of other authors such as [27] we have learnt a great deal about the process of roasting coffee, but we have failed to discover any waypoint that could help in determining the correct "ideal point" for terminating a roast at the point where the beans are most suitable for producing a pleasing brew.

That "ideal point" lies somewhere between 1^{st} crack and 2^{nd} crack but we see no significant event in the bean load that might pinpoint it.

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