The Coffee Roaster's Paradox

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Abstract—**This paper examines the engineering and application of different sensor methods to demystify the art that surrounds coffee roasting. 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. The sensor methods of, Online Calorimetry, Microwave Aquametry, and Raman Spectroscopy are analysed. The results are used to discuss and identify the problem facing expert coffee roasters as they attempt to roast the perfect coffee.**

Index Terms—**Coffee Roasting, Microwave Aquametry, Raman, Online Calorimetry.**

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. It is this step which imparts the greatest added value. The aim of the artisan coffee roaster is to chose the coffee and manipulate the dials just right in order to maximize desired flavours[1]. If you ask the artisan coffee roaster they will tell you that "there is an art to roasting the perfect coffee". In order for this to be true the coffee roasting must have some undefinable secret that only reveals itself after many years of coffee roasting experience. In this paper we look into the design and application of several sensors and sensor systems that show that the 'art' of coffee roasting is less of an unquantifiable guessing game and more of repeating a known. To put the master coffee roaster to the test and try to examine what is going on we ran a series of tests on roasting coffee that required; the construction and fine electronic control over a fluid bed coffee roaster; the use of temperature sensors and a specially chosen temperature ramp to thermally analyse the roasting coffee; use of microwave resonance, a network analyser, and image processing to monitor the coffee's changing permittivity to monitor changing moisture levels in the coffee; and using Raman spectrography.

II. HOW TO ROAST COFFEE

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, 6, 7]. Roasting is the process that takes green coffee seeds(usually referred to as beans) and heats them at temperates over 200C. At these temperatures the coffee undergoes numerous pyrolytic reactions developing the colours and flavours for which coffee is associated. There are multiple techniques that are used to subject coffee to roasting temperatures[1, 2]. The method used in this thesis is a custom fluid-bed coffee roaster.

Our fluid-bed coffee roaster consisted of a roasting chamber in which the coffee sits, a fan for blowing air to fluidise the coffee, and a heating element to heat this air. The air temperature was measured at various points in the roaster. The roaster's temperature was controlled via a LABJACK computer control interface and using a PID loop (figure 1). This setup allowed for flexibility in the roasting chamber as well as fine control over the roasting temperature.

III. THERMAL ANALYSIS

The first analysis was thermal. Thermocouples were positioned on the top and bottom of the roasting chamber giving the input air temperature and exit temperature. It was noticed that the raw temperature measurements, although useful for control, didn't express any obvious information about the condition of the beans. A solution was found by changing the heating method from a step to a ramp.

The temperature ramp roasting profile allowed us to produce a kind of online calorimetry we dubbed "Bean Load". The math used in the study of heat transfer is equivalent to Ohm's law. This means that heat flow in the roaster can be modeled as an electrical circuit. Adding coffee to the roaster is like adding an electrical load in series with roaster circuit, hence "Bean Load" is the load the coffee adds to the system. The concept of bean load is covered in greater depth in a previous paper [8].

A. Thermal Results

To better corroborate the bean load idea we developed a model of roasting coffee's 'bean load' in SPICE. The comparison of the model and the measured results (figure 2) showed that most of what is measured in the coffee's "bean load" was energy lost to evaporation.

The bean load results show a repeatable, and with the exception of a slight increase in endothermic activity at first crack, featureless progression.

IV. MICROWAVE AQUAMETRY

What do you get when you cross a stainless steel tube, a network analyser, a short copper wire, and a third of a cup of coffee? Our second measurement method, was the online microwave aquamertry of roasting coffee. Microwave aquamertry is a technique that measures moisture in substances by the interaction between microwaves and water.

Microwave moisture measurement techniques can be divided into four categories[9, 10]: the 1-port open-ended method[11, 12, 13], the 2-port transmission method[14, 15, 16, 17, 18, 19, 20], and 1- or 2-port resonant methods[21,

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[1] as coffee flavour is a subjective topic, for the purposes of this paper coffee is considered "perfectly roasted" when it reaches a point just before second crack

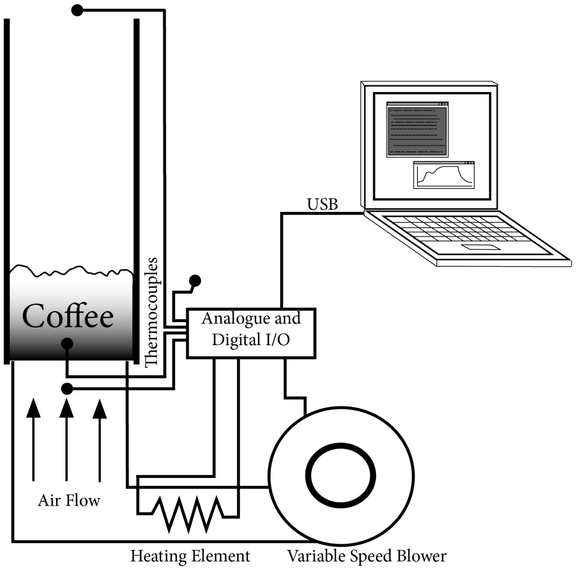

Fig. 1. Diagram of roaster function set up for thermal analysis.

22, 23, 24, 25, 26]. The technique used in this paper is a resonant technique that uses cavity perturbation to find the permittivity of a sample. This works by measuring the change in the resonant frequency and Q of a cavity when it is empty and then when a sample is present [10, 23, 27]. To find the sample's exact permittivity this technique relies upon some assumptions[2] being met in the experimental set up. Due to limits in coffee roaster design these assumptions could not be met. Therefore the results of this experiment were qualitative.

We designed a chamber —to hold roasting coffee— and modified the roaster setup facilitate microwave measurement (figure3). We chose a 1-port resonator as our measurement method, this was because of the physical constraints. Our roast chamber is made of stainless steel and acts as the resonant chamber. The hot air for roasting is pumped through perforated stainless steel disks at both the top and bottom of the chamber. The microwave energy is admitted in the side wall connected to a coupling structure. As our roast chamber is not ideal for making moisture measurements we did not seek to measure the absolute moisture or permittivity of the coffee. We wanted to identify the loss of moisture in the coffee by watching the change in a resonant peak during the roast.

A. *Microwave Results*

Obtaining any usable results out of this system was difficult. This was due multifaceted changes that occur during coffee roasting. The approach that we eventually used was to stack sequential network analyser measurements into an array forming an image. The a more detailed explanation of this approach can be found in our previous paper [28]. The setting the data in this structure has two major advantages. Firstly it allows for two dimensional filtering improving the signal quality. Secondly it creates a tool for easy visual inspection of the various changing frequency modes in the resonate cavity.

The result of these measurements was a graph of changing resonant frequency with roast time (Figure 4). In this graph we see the changing permittivity of the coffee in the roasting chamber. Initially there is a spike caused by the chambers rapid change in temperature. After this initial spike the permittivity starts to fall. We attribute this fall to the coffees decreasing moisture level. The moisture loss measured was shown to agree with the moisture loss predicted by the spice model.

The microwave resonance results show a repeatable near featureless progression.

V. RAMAN SPECTROMETRY

The third arena of investigation was to observe the surface chemistry of the roasting coffee using a Raman spectrometer. Raman spectroscopy is a spectroscopy technique that is able to discern the chemical makeup of a substance. It does this by observing, a set wavelength of light's inelastic scattering off the surface of the substance. A benefit of using Raman spectrometry is the flexibility of the setup. An external probe on the particular spectrometry allowed for the online measurement of the coffee during roasting (Figure 5).

Initial testing on coffee was done on individual beans on the spectrometers translation stage. A series of tests were done on coffee of increasing degrees of roastedness. This showed two things. First all the Raman spectra we were trying to measure was being drowned by fluorescence. Second there was a strong correlation between roastedness and average fluorescence.

Not being deterred by the lack of Raman spectra we decided that moving to online test was worth attempting simply to trial online measurement techniques. Even with no Raman to speak of the changing fluorescence had the potential to be useful. The major engineering challenge in making these measurements was consistency. This was a problem as the Raman spectrometer had a fixed focal point and the coffee was relatively large and in motion. This in turn meant that a different result would be produced every time the fluid-bed was stopped to make a measurement. A simple solution to this was keep the fluid-bed moving during Raman capture. Keeping the beans moving and extending the integration time of the sensor produced a consistent "Blur" of average fluorescence.

Using the averaged Blur measured by the Raman spectrometer produced the result in figure 6. What is shown is a near linear increase in average fluorescence. It shows little to no change around first crack. Near second crack there is a deviation. Unfortunately this deviation is not as useful or repeatable as it appears. Firstly it happens inconsistently and well before second crack. Secondly on repeat observation of the individual results it appears to be less a function of the surface chemistry and more likely an artifact of the measurement process. In the end this process did not allow us to find the desired Raman based transient that we were looking for. However like the other measures tested it demonstrated the coffee progressing (during roasting) in a consistent fashion over the course of the roast.

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[2] The electric fields in the cavity must be negligibly changed by the sample, and that the electric fields typically need to be uniform over the volume of the sample.

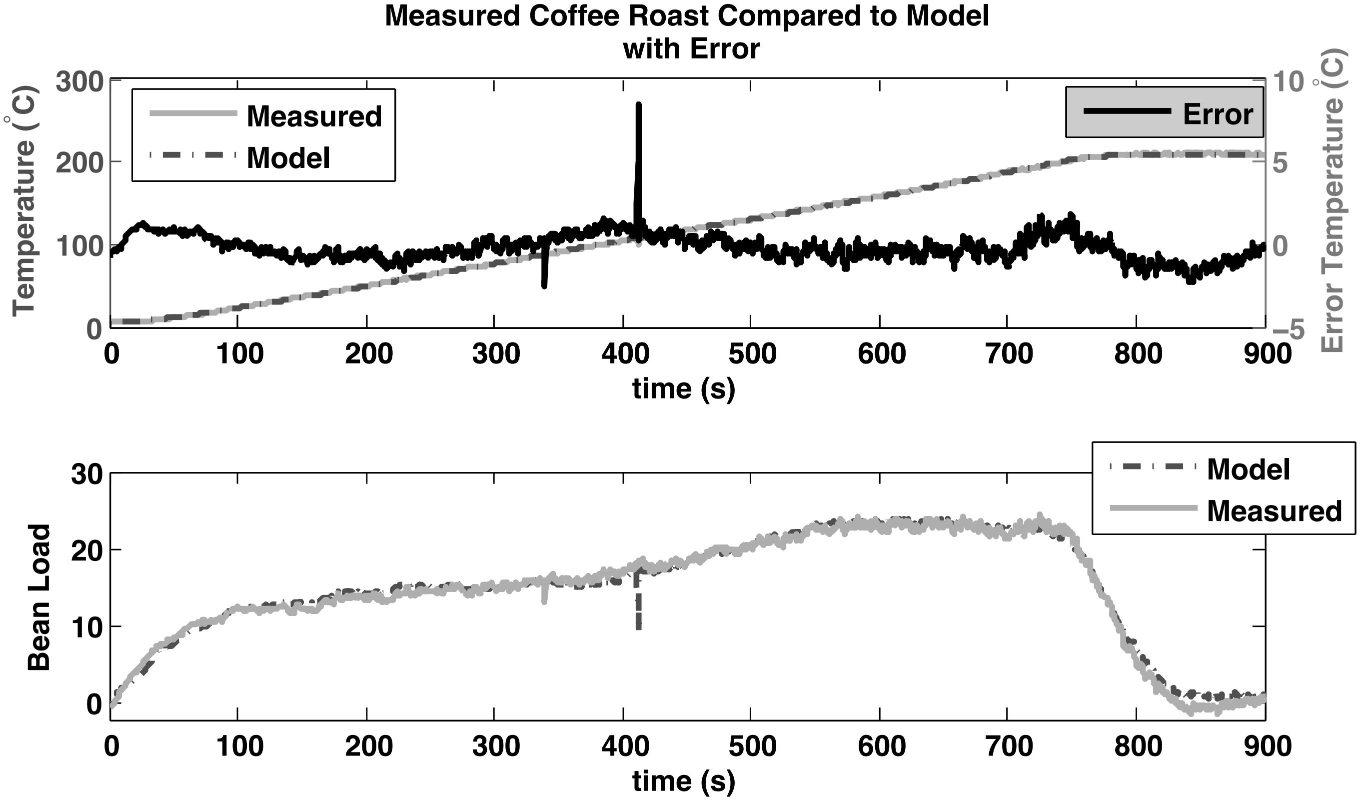

Fig. 2. Top: Measured temperature compared with modeled temperature. Bottom: ”Bean Load” measured vs. modeled

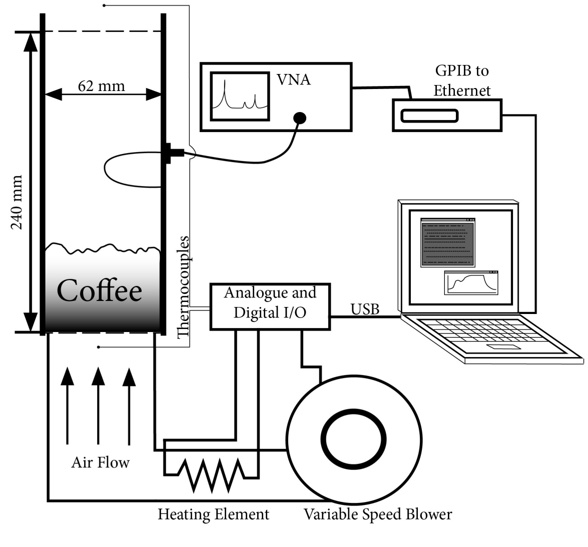

Fig. 3. Diagram of roaster function set up for microwave resonance measurement.

VI. Collating Results

At this point we have tested three different sensor methods to observe the roasting coffee. All three methods showed a smooth near featureless progression through out the coffee roast. It may appear that nothing useful has been found in these results however the reverse is true. These results combined with (non-real-time) analysis done years ago[29], we are relatively sure that there is no chemical or physical marker of coffee being roasted to the ideal degree. This means that a master roaster cannot be depending on some magical

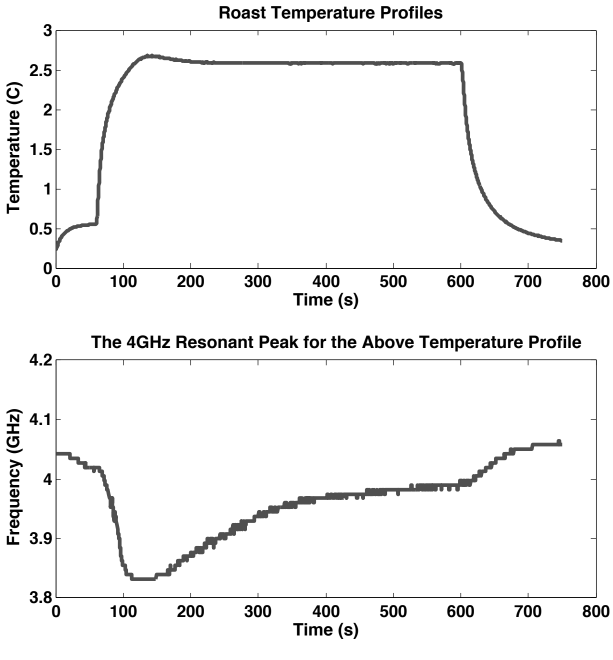

Fig. 4. Top: Step temperature roast profile. Bottom: Changing frequency of resonant peak during roasting.

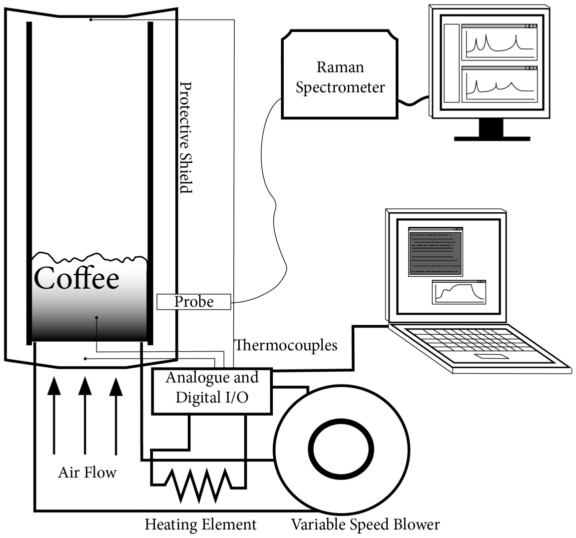

Fig. 5. Diagram of roaster function set up for measurement using a Raman Spectrometer.

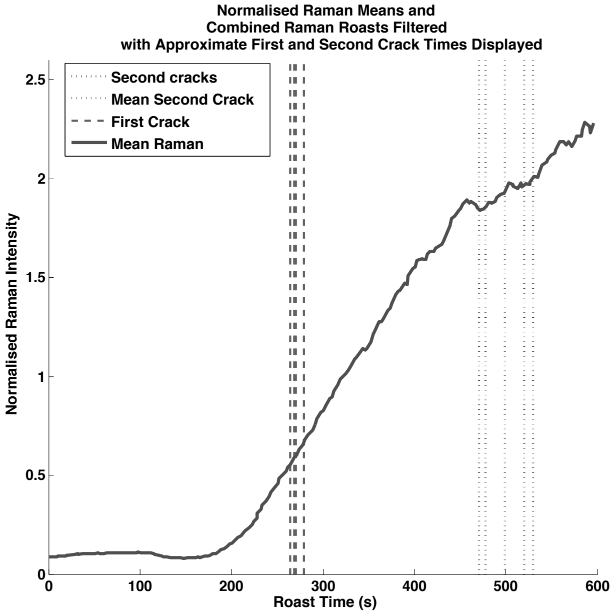

Fig. 6. Shift in average Raman intensity as the roast progresses.

end or roast way-point. The question then remains—what does the expert coffee roaster do to ensure well roasted coffee?

Our favored explanation for how coffee roasters "get it right" is twofold; relying on repeatability and stretching the target. Firstly by knowing the characteristics of the input coffee and building a look up table knowledge of how different coffees behave during a roast allows the expert to hit the target by repetition. Secondly, by widening the roast spread(Figure 7). This method allows the roaster to hit the the target by waiting until the first snaps of second crack and rapidly ending the roast there by ensuring most of the coffee ends the roast at the desired degree of roast. An analogy we found that best illustrates the master roasters problem is the archer's paradox [3]. The major unknown in archery is the arrow. In coffee roasting its the coffee itself. In this day and age the master coffee roaster can have a minute level of of control over their roasting machine however what is more difficult to control is the behaviour of the coffee. A given coffee's behaviour during roast is dependent on many factors including but not limited to, geographic origin, processing methods, sorting, and container transportation. The solution then is to either learn all you can about the condition of the beans or widen the spread.

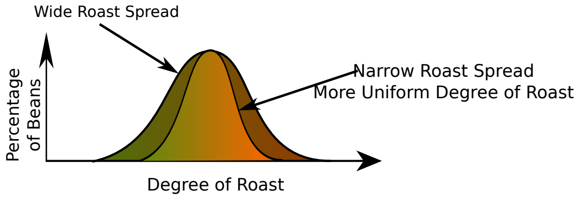

Fig. 7. This is the roast spread section

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[3] There exists a paradox in the art of longbow shooting; when the arrow is shot it should be deflected by the arm of the bow sending it off away from the target, however the arrow manages to curve around the bow and heads toward the target. How the arrow does this is by flexing around the bow arm creating a precessive wobble as the arrow flies through the air. In order for the archer to then accurate and precise they must use known equipment as it would be impossible to predict the exact flight of the arrow otherwise. There is a YouTube video by Smarter Every Day the eloquently explains this idea[30].

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