Abstract—A first investigation into the use of microwaves for the non-destructive testing for the presence of black heart cavities is presented. Additionally a potato’s complex permittivity data between 0.5 GHz to 20 GHz measured using a coaxial sensor and the recipe for a potato phantom are also presented. Electromagnetic finite-difference time-domain simulations of potatoes show that changes to how microwaves propagate through a potato caused by a cavity can produce measurable changes in $S_{21}$ at the potato's surface of up to 26 dB. Lab-based readings of the change in $S_{21}$ caused by a phantom cavity submerged in a potato phantom liquid confirms the results of the simulation, albeit at a much reduced magnitude in the order of 0.1 dB.

I. INTRODUCTION

Demand for high quality produce e.g. potatoes from retailers and their customers has resulted in these produce being subjected to rigorous quality control checks. For example, when improperly stored post-harvest without enough oxygen, potatoes exhibit a decay of their centres as their cells asphyxiate, a condition known as black heart. Current methods for detecting black heart in a batch of potatoes are reliant on the statistical sampling and manually processed destruction. It’s estimated that these destructive tests accounts for 0.5% of the post-harvest wastage volume, with a net value of more than GBP 10 million.

As a means to reduce such wastage, technologies for non-destructive testing (NDT) and their automation have become important in recent decades [1]. Possible technologies capable of NDT beneath a potato’s surface exist, but they come with either safety issues e.g. x-rays [2], or operational or throughput limitations e.g. ultrasound [3], [4].

An alternative is microwave imaging which thus far has yet to have its NDT capabilities in a food processing setting explored. In this paper we will present a first evaluation on the use of microwave radiation in the NDT for the detection of black heart cavities in potatoes.

II. SIMULATING MICROWAVE PROPAGATION THROUGH POTATOES

To begin the study, how microwaves propagate through potato with and without black hearts needed to be understood. This part of the study involved the measurement of a potato’s complex permittivity, the values of which were then used in a computer simulations as well as in the creation of a potato “phantom” that would be used in further experiments in lieu of a real potato.

A. Complex Permittivity of Potatoes

The complex permittivity of the Melody variety of potato was measured with an Agilent 85070-Perf coaxial sensor (Fig. 1) using a method detailed in [5]. A potato from a store bought batch had a patch of skin removed to provide a flat surface for the 1.6 mm diameter sensor to contact. Calibration of the coaxial sensors were carried beforehand using the reference liquid procedure from [6].

![Fig. 1. The two coaxial sensors used during this work: NPL 7 mm (left) and Agilent 85070E-Perf (right).](image-url)
B. Simulation Setup

With the measured values of a potato’s complex permittivity in hand, the data was used in a 3D electromagnetic Finite-Difference Time-Domain (FDTD) computer simulation of microwaves propagating into and through a potato. The simulation was carried out using commercially available software (CST Microwave Studio). The aim of the simulation was to assess what changes the presence of a black heart cavity would have on the propagation of microwave radiation through a potato. This information would then be used to inform the design of the setup required for the lab-based measurements.

The simulation consists of a potato modelled as a 70 mm diameter sphere centred on the simulation space’s origin (Fig. 3 and Fig. 4). The black heart cavity was modelled as a 10 mm sphere with the electrical properties of a vacuum. Microwave radiation, linearly polarised along the $y$-axis, was projected along the $x$-axis into the potato with an E-band (3.3 GHz to 4.9 GHz) waveguide. The waveguide’s opening was drawn such that its edges matched that of the spherical potato’s surface. In addition a hemispherical shell was added to the waveguide structure so that the waveguide facing side of the potato was encased. This was initially done to reduce the effect of surface waves that appeared in earlier simulations that did not have it. Both the waveguide and shell material’s were defined as a Perfect Electric Conductor (PEC).

Two sets of simulation were run. One without a black heart cavity (Fig. 3) and one with (Fig. 4). Comparison of the results from the simulations was carried out by looking at the electric field strength along the $xy$- and $xz$-planes of the simulation space and by calculating the change in measured transmission magnitude from six virtual probes placed on the surface of the potato’s exit face i.e. $\Delta \text{mag}(S_{21}^{\text{Sim.}}) = \text{mag}(S_{21}^{\text{Void present}}) - \text{mag}(S_{21}^{\text{No void}})$.

C. Simulation Results & Discussion

Fig. 5 shows the simulated electric field strength in the $xz$- at 3 GHz when a black heart cavity is (a) not present and (b) is present. With no cavity present, the fields are seen to show that the potato behaves in a manner of a lossy convex lens, bringing radiation to focus whilst absorbing it too. Microwave radiation is transmitted out from the potato mainly from the point directly opposite the waveguide in the $xz$-plane. The presence of the cavity reduces the amount radiation reaching the surface at points directly behind it as they are cast in the cavity’s shadow. Regions surrounding this point receive an increase in radiation due to the cavity (with its lower permittivity than the surrounding potato) behaving as a divergent lens, spreading radiation that wasn’t reflected off its first interface.
The probe data is plotted in Fig. 6 as $\Delta \text{mag}(S_{21}^{\text{Sim.}})$ against frequency across the E-band. As expected from the previous analysis probe x sees a decrease of 5 dB across the band due to its location directly behind the cavity from the waveguide. Probes xz, z and xyz all show increases ranging between 10.8 dB and 26.7 dB across the E-band, again as expected due to the cavity spreading radiation away from the point directly opposite the waveguide. Probe y sees effectively no change across the band, this may be due to the stronger fields in the $xy$-plane (figure not presented) close to the edges of the shell where probe y is located.

These simulation data shows that values of $\Delta \text{mag}(S_{21}^{\text{Sim.}})$ as large as 25 dB may be observed. The most reliably detected changes come from the probes located in the $xz$-plane. By comparing which probes measure an increase, decrease or no change, a cavity’s presence and location may be deduced. Using these results, a lab-based experiment was designed.

### III. MEASUREMENT OF $\Delta S_{21}$ IN POTATO PHANTOM

#### A. Potato Phantom Liquid

The need for a potato phantom was to allow the repeatable measurement of an object of known shape and size, that also exhibited the dielectric properties of a potato at the observed frequencies. Real potatoes suffer from dehydration over time changing their internal properties, in addition to coming in a variety of sizes and irregular shapes. A solution consisting of, by weight, 6.8 % polysorbate 80, 1.1 % sodium chloride and 92.1 % deionised water was created to perform as a potato phantom liquid. Measurements with the 7 mm NPL coaxial sensor (Fig. 1), using the procedure of [5] show that it was successful in reproducing the complex permittivity of the potato between 2 GHz to 4 GHz (Fig. 7 and Fig. 8). The agreement between the real and imaginary components of the potato phantom and the measured potato values is within 1.2 % and 10 % respectively.

#### B. Experimental Design & Setup

To attain repeatable measurements, the setup shown in Fig. 9 was designed, based on the setup used in computer simulation of Section II-B. In this a waveguide transmits microwaves into a HDPE plastic bottle (external diameter: 60 mm, internal diameter: 58 mm) that is filled with potato phantom liquid from the previous subsection. At the same height as the waveguide, wrapped around the bottle’s remaining circumference, a flexible printed circuit board (PCB) with seven equidistantly separated 3.3 GHz Murata SMT antennas mounted on are used to measure the microwaves that were able to transmit through the bottle. An expanded polystyrene cylinder 22 mm in height and 22.4 mm in diameter was used as a black heart cavity phantom.

Several design choices and changes from the simulation setup were incorporated based on the results of the previous section. Firstly, the waveguide was designed to be dielectrically loaded with Macor® ceramic glass. This was to reduce the waveguide’s dimensions to 10.1 mm × 23.2 mm and to improve impedance matching between it and the potato. Secondly, it was decided to only look for changes in the microwave transmission in the same plane as the waveguide. Thirdly, for practical reasons the potato is represented as a cylinder rather than a sphere.

To obtain a reading, a transmission reading is taken at the antennas without the cylinder submerged in the phantom liquid, $\text{mag}(S_{21}^{\text{No cyl.}})$, and another with it submerged in the bottle’s centre to the depth of the waveguide and antennas, $\text{mag}(S_{21}^{\text{Cyl. present}})$. A single reading of is then $\Delta \text{mag}(S_{21}^{\text{Exp.}}) =$
imaginary permittivity, \( \varepsilon' \)

Polystyrene of balsa rod

The mean readings of \( \Delta \text{mag}(S_{21}^{\text{Exp}}) \) from the seven antennas and the standard deviations are given in Table I. As expected the antennas located most behind the cylinder, i.e. 3 to 5, observed a decrease in received transmission when cylinder was present. However this was at a level much lower than expected based on the simulation results, −0.17 dB for antenna 4 compared to −5 dB for probe x. The remaining antennas were expected to see a positive \( \Delta \text{mag}(S_{21}^{\text{Exp}}) \) due to reflected microwaves. Indeed that is seen in antennas 6 and 7, measuring an increase of 0.13 dB and 0.10 dB respectively. Antennas 1 and 2 see a decrease however.

These first results demonstrate that detection of a phantom black heart cavity is possible by looking at the change in detected transmission levels of microwaves. The smaller than expected \( \Delta \text{mag}(S_{21}^{\text{Exp}}) \) could be placed down to losses in the lab-based setup. Mismatch between the curvatures of the waveguide and bottle limits how well the microwaves are transmitted into the bottle. The SMT antennas are also not 100% efficient in receiving microwave radiation in the same way as the virtual probes in the simulation are. Further reductions may be accounted for from losses in the cables and PIN switch. This asymmetry in the readings of antennas, 1 and 2, and 6 and 7, may be caused by misalignments in the setup.

Future work will look into the measurement of the microwave’s phase component to detect presence of black heart cavities as well as making improvements to the setup.

**IV. CONCLUSIONS**

In this paper we describe the first attempt of the use of microwaves for the non-destructive testing of black heart cavities in potatoes. Initially the complex permittivity of the Melody variety of potato was measured, from which the values were used in an EM FDTD simulation of a spherical potato without and with a cavity. The simulation data showed that changes in the amount of radiation reaching the surface between the two should allow the detection of a cavity. Lab-based measurements using a potato and cavity phantom also saw changes, albeit at a lower level than the simulations.

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