MAGNETIC RESONANCE IMAGING TECHNOLOGY FOR PROCESS CONTROL AND QUALITY MAINTENANCE IN FOOD QUALITY OPERATION

S.Divya[1], D.Thyagarajan[2], G.Sujatha[3]
[1] B.Tech (Food Technology), College of Food and Dairy Technology
Koduvalli, Redhills, Chennai-52, India
[1]yadiv711@gmail.com
[2] Faculty of Food Science, College of Food and Dairy Technology
Koduvalli, Redhills, Chennai-52, India
[2] drthyagu2002@yahoo.com
[3] Electrical Engineering department, College of Food and Dairy Technology,
Koduvalli, Redhills, Chennai-52, India
[3] sujatha-boosham2011@hotmail.com

***Abstract*-This paper investigates the process optimization of various food processing methods such as drying, freezing, freeze drying, extrusion, rehydration of liquid foods, slurries, and suspensions, dry powders and baked products etc., which is an essential step in the optimization of many food manufacturing processes. This article will discuss about the quality factor associated with cellular tissue and also in chocolates. And also this article will give an idea about the on-line MRI for process control and quality assurance in the food processing operations and controlling the quality parameters and act as on-line sensors in quality control of intermediate or final products. The single magnet design and NMR protocol will differ for various applications and it is necessary to adapt a spectrometer operation to each specific application. Magnetic Resonance Imaging (MRI) is an emerging technology in foods, and it allows the interior of the food to be imaged noninvasively and non- destructively. These images can then be quantified to yield information about several process and material properties ranging from the composition of a material to the physical structure of the material. The signal detected by a MRI machine varies depending on water content and local magnetic properties of a particular material. Different substances can be distinguished from one another in the study image. This technology provides a real time internal process control for the food industry. This article will also discuss about the various techniques such as solid – imaging techniques for quality check of dried-food products and functional imaging techniques for optimizing the food crops in the field using MRI technology.**

Keywords: MRI, NMR, process optimization, spectrometer, superconductors.

I. INTRODUCTION

The possibility for exploiting MRI as an online sensor for process control and quality assurance throughout the food manufacturing sector are very great, and the term online generally refers to the real time measurement during processing. The optimization at all stages of production is possible right from the optimization of crop yield and post harvest processing for improved food quality, safety, and energy efficiency in many processing operations, and to do this various techniques are used accordingly such as fast imaging techniques like FLASH imaging, FAST imaging, EPI(*echo planar imaging*), projection imaging. And we all aware of that, the chemical composition of a food are one essential factor determining its quality and for this chemical shift imaging (*CSI*) is followed. This article will discuss about the various process optimization and process control of food commodity right from the cellular tissues to the dried and rehydrated products.

II. MRI AND PROCESS OPTIMIZATION

Once a food crop has been harvested, it will undergo some form of industrial processing such as extrusion, cooking, drying, freezing, freeze drying. The noninvasive attribute of MRI makes it almost ideal tool for monitoring the processing operation, and it is technically demanding to use MRI in a dynamic mode to follow changes in food materials in real time as they undergo various processing methods. And this technology is well suited for the real time and on-line investigation of all the food processing operation.

Depending on the imaging protocol, these include spatial maps of spin number density, relaxation times, magnetization transfer rates or self-diffusing coefficients. And the NMR parameters can be converted into maps of quantities such as moisture content, temperature, and food quality needed for optimizing food processing conditions. A dry cooking process is used for industrial roasting, baking, drying, toasting. In the baking oven hot air is blown over the food and in this all the manufacturing operation has to be optimized to produce the desired food quality with minimum cost. Reference [1] shows the Process design and analysis by combining a theoretical simulation of the entire process with selective measurement of parameters values.

A. MRI Drying Studies

It is, in principle to use MRI to investigate the drying process. Diffusion model is one of the earliest model for drying studies, since this model has number of difficulties and more complicated and therefore MRI becomes apparent by providing real-time noninvasive maps of the moisture distribution W(r, t). And a study undertaken as in [2] involved drying an agar gel which is dried in a radially symmetric airstream of controlled humidity, velocity, and temperature inside the MRI probe. It exhibits many of the characteristic features of food material and expected to conform to a diffusion controlled drying mechanism. The drying of extruded pasta is investigated with MRI [3]. It shows that drying too fast or too slow will cause differential shrinkage, bending, and stress cracking to the pasta, and also optimizes the drying conditions by understanding the drying kinetics and it is investigated using radial microimaging. To permit unhindered shrinkage and a radially symmetric flow of dry air around the pasta, a specially designed holder is required for a pasta freezing and also for drying shown in (fig:I).

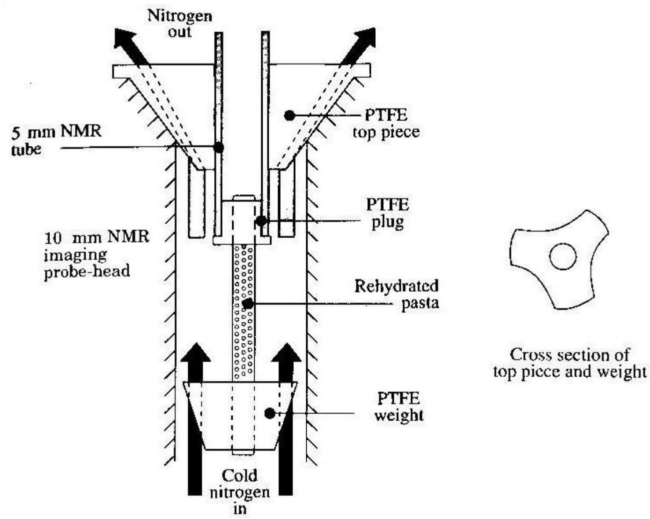

Fig I: Probe Arrangement for the Drying and Freezing of Cylinders of Pasta and Potato.

Reference [4] shows the MRI to study the moisture profile during the air drying of raw potato cylinders and two-dimensional spin wrap imaging sequence were used since water affect the quality and structural changes in potatoes during storage, handling, and processes such as freeze drying ,freeze thawing and cooking . A study on corn kernel using three – dimensional imaging and explored the origins of stress cracking in kernels and determined the effects on crack development of factors such as variety, drying temperature and moisture content [5] [6]. While considering the drying of plant tissue [7] [8], have imaged the distribution of water in sultana grapes before and after drying for 24 hr at 40°c. The Vapor-phase diffusive transport mechanism has been studied [9]. The vapor-phase transport for low-water-content porous media [10].

B. Rehydration

Most dried foods are rehydrated by the consumer before consuming it and so it is very important to ensure that the rehydrated product has a satisfactory quality. The stickiness and cohesion after rehydration are important quality factors. MRI can assist in optimizing the choice of raw material by providing detailed information about the moisture profile within individual spaghetti strands during rehydration and to do this, dry spaghetti, extruded from various types of wheat, was immersed in water at 80°c and samples removed every few minutes for radial imaging with a spin –echo sequence [11]. A STRAFI (*stray- field imaging*) solid-imaging study on the rehydration of a starch glass by liquid water and by water vapor has been reported [12]. The MRI has been used to compare the rehydration of wheat grains by boiling and steaming [13]. And the moisture images were obtained by spin-echo signal for transverse relaxation and by calibration of the spin density map with gravimetric measurement of water content. It was found that during boiling, water penetrates evenly into the wheat grain from all points on the boundary, including the inside of the crease. In contrast, steaming gives slower rehydration and spatially uniform water content throughout the grain gets gradually increased. The MRI image of the uptake of water into dry beans has been studied [14]. Here the major processing requirement is to optimize the water uptake rate and water holding capacity while decreasing splitting of the beans. If the beans split, the seed coats often separate and expose the cotyledon. The processing equipment usually discards these beans, causing reduced yields. If exposed cotyledon escapes detection and end up in the product they cause starching and cause change in the heat transfer coefficient, increasing thermal processing requirement. And it won't comply with quality standards. The MRI study gain insight into the rehydration kinetics. Result showed that water uptake by the undamaged beans occurs in two phases. The first appear to be controlled by natural barriers, such as the seed coat, and the rehydration dissolves the middle lamella. The released seed coats are water permeable and become taut as the cotyledon expands during rehydration. As with potato drying experiment the intensities were proportional to the moisture content and it was found that the hard layer produced on the outside of the potato during drying (*i.e., through case hardening*) acted as permeability barrier to rehydration, which was therefore much slower than the initial stages of drying. The structural changes induced in the surface layers by case hardening also resulted in much slower and smaller volume expansion during rehydration than the volume shrinkage observed during drying. And this emphasizes the importance of incorporating the case hardening in the theoretical models of tissue drying and rehydration [15].

C. Freezing Drying

Freeze drying involves the removal of water by sublimation of ice into vapor under vacuum. The sliced food is frozen and the ice removed by sublimation under vacuum is what is conventionally called the primary drying stage. This is followed by the secondary drying stage, where residual unfrozen water is removed by heating the product under vacuum. MRI has been used to follow the kinetics of the primary stage of the freeze-drying of potatoes [16]**.** Ice gives no signal in MRI but here the unfrozen water distributed among microscopic compartments in the frozen core of the food matrix is sufficient to provide a signal under high receiver gains. A simplified theoretical model of the primary freeze-drying stage that gives a reasonable fit to the MRI potato data is based on the assumption that the sublimation process proceeds by a series of pseudo steady states where all the heat supplied to the ice front is used for sublimation. Heating ovens during the baking of cookies and bread is expensive, so maximizing the throughput while maintaining quality is an industrial priority. Imaging the baking process is also difficult because fat contents are usually high and water contents become very low and transverse relaxation time is short, especially toward the end of the baking process. The localized spectroscopy and MRI is used to study void formation, lipid migration, and moisture loss during cookie baking in the united states, the result show an increase in moisture content in the center of the cookie but little lipid migration [17]. The quantified data of the moisture migration is done by calibrating image intensity against gravimetric water loss. Their lower limit on detectable water content is about 15%, which can be compared to a typical moisture content of 3% to 4% in a baked cookie. And optimizing the temperature and blend of frying oils is especially important to minimize the oil loss, maximize the quality, and in responding to the changing consumer fat consumption patterns and the trend to less saturated oils [18]. By using MRI the image of oil-water interfaces in 2-cm-diameter potato cylinders after frying 6 min at 190°c has been studied and compared the result with SEM (Scanning Electron Microscopy) [19].

D. Extrusion

Extrusion is perhaps one of the least understood food processing operations, yet its uses are widespread throughout the industry because it is a continuous operation, very flexible in its range of application, and gives end products of reproducible quality. And During extrusion process, a complex series of physical and chemical changes take place, such as mixing, gelatinization, denaturation, evaporation, flavor production and flavor loss, and rheological changes. understanding these factors and mathematically modeling these complex and rapid changes is a major challenge.MRI can greatly assist in providing real time noninvasive images of the flow within the extruder and potentially, spatial maps of other NMR parameters such as relaxation times, chemical shifts, and diffusion coefficient as well as images of temperature and/or chemical changes. The various measurements were made by McCarthy and co workers with a special extruder made of nonmagnetic materials and operated inside the magnet of the NMR spectrometer.

III. MRI AND FOOD QUALITY FACTORS

There are many factors that determine the quality of a food Such as color, taste, aroma, texture, and chemical composition, including the concentration of factors such as vitamins, sugars, and lipids. The extent of denaturation and gelatinization of biopolymers and the changing phase structure of the food caused, for example, by polymorphic transitions in lipids and fats, crystallization of sugars, and retro gradation processes associated with biopolymers. Not all quality factors are amenable to MRI analysis. MRI being used to monitor changes in food quality can be found in most classes of food, including confectionery, fruits and vegetables, fish and meat, and cereal and dairy products.

In general the long term storage of fat containing foods can be affected by fat crystal growth and polymorphic transitions in the solid fat phase. [20] NMR measurements of the transverse relaxation times based on an FID sequence are now used routinely for the determination of solid-liquid fat ratios. In chocolates MRI signal originates from the protons in cocoa butter and milk fat. The amount of solid and liquid fat in the chocolate will obviously vary with temperature. Six polymorphs have been identified by differential scanning colorimetry where, slowly cooling cocoa butter produces the more stable number 5 polymorph, whereas more rapid cooling gives the less stable number 3 or 4 polymorph [21]. The larger amounts of a solid in amorphous phase exhibit greater chain stability and a longer transverse relaxation time [22]. The blooming is an important quality factor caused by polymorphic transition and long term storage and result in loss of surface gloss change in flavor and hardness. The migration of liquid lipid components between two phases in multilayer confectionery products greatly affects the long term quality of the product. A study on the image of the transport of liquid lipids into the chocolate in a model lamellar two-layer chocolate product consisting of a layer of hazelnut oil and sugar layered over with dark chocolate [23]. And the time course of the lipid migration was followed over an 84-day period for two samples stored at 19 and 28°c. At 19°c the liquid lipids tend to accumulate at the interface between the hazelnut oil and chocolate layers. In contrast, at 28°c the lipid accumulates at the chocolate surface.

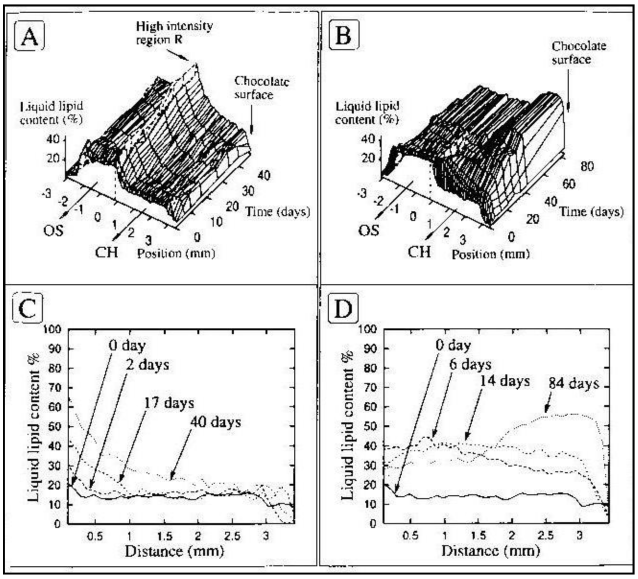

Fig II: Time course of the liquid triacylglycerol content in chocolate.(A)experiment at 19^{0}c; (B) experiment at 28◦c; (C)migration profiles of the liquid triacylglycerol in chocolate at 19 ◦c; (D)migration profiles of liquid triacylglycerol in chocolate at 28°c

A study has been done on the lipid transportation and its effect on the quality of the product during the migration of fat into the bread from peanut butter using MRI [24]. And also the lipid transport is studied during the separation of cream from milk over a 9-h period using the NMR imaging in dairy products [25].

A. Quality Factors Associated With Cellular Tissue

Reference [26] shows a study on MRI spin-echo imaging of whole fresh and frozen cod for determining the differences in the water binding capacity and its effect on the fish texture noninvasively. This is an important storage problem because cod shows marked changes in texture due to protein aggregation during frozen storage, thereby making the fish unpalatable. And in bacon manufacturing industry variation in the quality of cured meat, such as pork, during brining, is of primary interest. And the two-and three- dimensional ^{23}Na imaging has been used to image the spatial distribution of brine in cured rabbit muscle and in tumbled ham[27].The MRI manganese diffusion studies act as a indirect method to follow the diffusion of sodium and chloride in to the meat [28].

In cereals the distribution of lipid and solute concentrations in cereal grains is one important quality factor amenable to MRI analysis**.**Ishida and co-workers (national food research institute, Japan, unpublished conference abstract) have used chemical shift micro imaging and localized spectroscopy to image the production and spatial distribution of maltose and other metabolites in germinating barley seeds, which affects the quality of beers and spirits.

In fruits and vegetables number of feasibility studies has used MRI to monitor fruits and vegetable quality, such as bruising in apples, pears, onions, and peaches. [29] [30] shows a study which is carried on the deterioration of apples in storage. And a detailed analysis of the origins of image contrast in bruised apples has been made by McCarthy and co-workers and suggests that gradient –recalled images may be more useful in future online MRI sensing of bruising apples.

IV. SOLID IMAGING TECHNIQUE FOR TRACKING THE QUALITY OF LOW MOISTURE FOODS

The end product of food processing operations such as drying, baking, and freeze-drying result in low moisture content shelf stable products. Although conventional imaging methods can be used to follow moisture migration during the early stages of baking or drying, this is not true during the later stages, as the system becomes more solid like and the transverse water proton relaxation times shorten to less than 1 ms. So that solid imaging techniques comes in to picture to overcome this thing. Many baked foods, such as bread and cookies, not only have a low water content but also a very high porosity created as gas replaces water during the baking. These highly heterogeneous, porous solids are difficult to image conventionally because of the low water content and the massive susceptibility broadening effects created around the gas pores, but solid imaging techniques are able to circumvent these difficulties and could perhaps be used to image the final stages of the baking process. And some of the solid imaging techniques are stray-field imaging (STRAFI), phase encoding solid imaging (PSI), and sinusoidal gradient-echo imaging and finally combined multipulse-sinusoidal gradient echo imaging. In food cryopreservation, either in the chilled or frozen states, is another obvious area where solid imaging could have an impact. Because of their heterogeneity and compositional complexity, there is rarely a single liquid-solid phase transition as the food is cooled. Instead, different microscopic compartments and fractions in the food will freeze, or crystallize, at different temperatures. Solid imaging offers the possibility of observing the spatial distribution of these transitions as the food is cooled [31].

V. FUNCTIONAL IMAGING

Optimizing the production of food crops in the field requires detailed knowledge of the effects of environmental factors on plant development. These environmental factors include osmotic stress caused by drought, as well as nutritional requirements and the effects of herbicides, pollutants, and disease. By permitting noninvasive, in vivo monitoring of the whole plant as it develops under realistic environmental conditions, functional imaging has become a powerful tool in the whole-plant armory.

There are various experimental protocols for imaging a living plant under realistic environmental conditions.

- One possibility is to bring the spectrometer to the plant which is growing in the field by using portable low-field (e.g., 10MHz) permanent- magnet spectrometers in which the magnetic poles are split so they can be placed around the plant stem [32]. But this can be suitable for flow imaging but unsuitable for chemical shift imaging at high resolution, where high, well- shimmed fields are needed.
- The other approach is to bring the plant to the spectrometer, but here the problem is to maintain the root system bathed in nutrient and the whole plant in an environment of controlled humidity, temperature, and luminescence intensity.
- Final possibility is to use surface coils attached to various parts of the plant, and the recent commercial development of superconducting coils offer several possibilities for doing this[33].

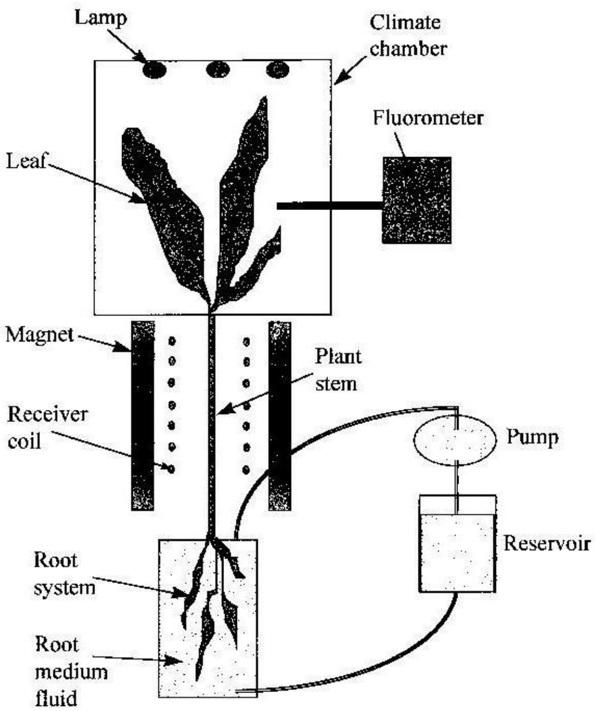

Fig III: Schematic of a probe arrangement suitable for whole-plant functional imaging.

The process of functional root imaging is done by placing a vessel containing soil and roots inside the spectrometer magnet, the development of a plant root system can be followed, noninvasively, in real time assessment [34] [35]. The relationship between the root development and water depletion zones set up in the soil as the root extracts water and nutrients can be studied quantitatively. The noninvasive aspect is mandatory because any disturbance of the soil by removal of a root can change the soil porosity, the spatial distribution of water and nutrient, and the distribution of microbiological population within it. A recent application of this underground functional MRI has been to follow the development of pine roots using three-dimensional images to distinguish the soil and root [36].The development and the physiology of underground crops such as carrots and potatoes can be imaged for understanding the irrigation pattern and soil type on the growth of carrots, potatoes, and other tubers.

VI. ON-LINE MRI FOR PROCESS CONTROL AND QUALITY ASSURANCE:

The possibility of exploiting MRI as an on-line sensor for process control and quality assurance throughout the food manufacturing sector is very great and the term *on-line* generally refers to real – time measurement during processing. The type of food material and the production environments vary so greatly that no single magnet design and NMR protocol will be suitable for all applications and it will be necessary to adapt spectrometer operation to each specific application.

The constraints imposed on all on-line NMR/MRI measurements by spin physics:

- The sample container should not be metallic, because radio frequency radiation does not easily penetrate metal.
- The conveyor and all components therefore need be made of nonferrous material.

The first step in on-line NMR is to polarize the sample in a constant magnetic field. Polarization involves the relaxation of longitudinal magnetization from zero to the equilibrium value determined by the Boltzmann factor temperature T in a field B_o. Here two magnets could be used, a high-field magnet one for polarization for a short time, and a lower-field magnet for on-line detection. And we can also redesign the conveyor system so that there is a reservoir of samples waiting in the polarizing field before entry on to the conveyor.

Once the sample is polarized, the next step is signal excitation. Here spin physics dictates that the sample has to pass through the excitation coil and the static magnetic field simultaneously and that the static and excitation fields must be in orthogonal directions. Electromagnets can generate higher fields but can have high power consumption and require cooling. Superconducting magnets give the highest fields, and therefore best signal-to-noise ratio with no power consumption but are very expensive and require filling with liquid nitrogen and helium. Finally, low cost, high-temperature superconductors would be the ideal for on-line applications. Rapid data collection and analysis are needed for real-time monitoring, and in some cases this could become the rate limiting step.

The standard design of NMR spectrometers, whereby the sample is placed inside a magnet and RF coil, is based on spectrometers, but however this standard configuration is not necessarily the best for on-line studies, especially with large samples. For much application inside-out design is more appropriate, in which excitation and detection does not have to occur inside the magnet and detector coil [37], and they found application in the oil industry. In Fig IV it shows a schematic of the basic features and how excitation and detection occur in the outer region.

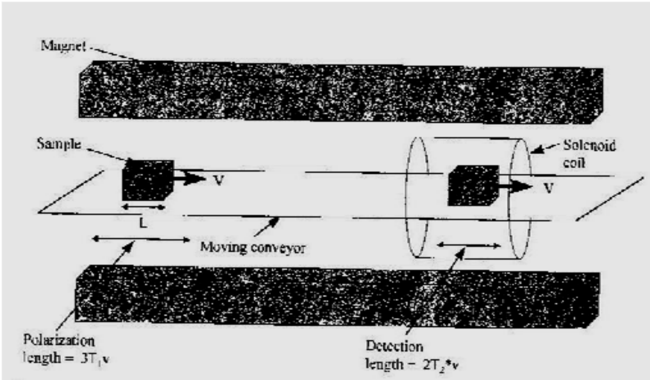

Fig IV: Conventional NMR apparatus with a solenoid coil adapted for use around a moving conveyor

And further designing aspects for on-line process control is discussed [38] about the use of NMR for on-line process control and quality assurance.

A. Non-spatially Resolved On-Line NMR

One of the first nonspatially resolved, on-line NMR instruments was developed [39] and it is used for monitoring the composition of a liquid stream using the chemical shift spectrum and the spectrum was recorded for every 6s using a continuous wave system and here the fluid was diverted through the spectrometer in a side-line arrangement and a small reservoir within the magnet was used for polarization. A similar side-line method has been reported [40] and used to monitor the fat content in flowing the meat pastes. [41] Described an on-line system that sits below the production line and samples from it by lowering a mechanical piston so that the sample falls into a cylindrical NMR sample chamber. After measurement, the sample is returned to the production line by raising the piston. A schematic of the apparatus is shown in Fig:V and this system is well suited for finer, dry products such as powders but could, in principle, be used with fluids. The measurement of an on-line FID of whole avocado travelling on a conveyor belt using a surface coil has been studied [42]. They showed that the oil/water spectral peak ratio was unaffected by velocities up to 250 mm/s. And a portable nonimaging spectrometer for quality assurance has also been described [43].

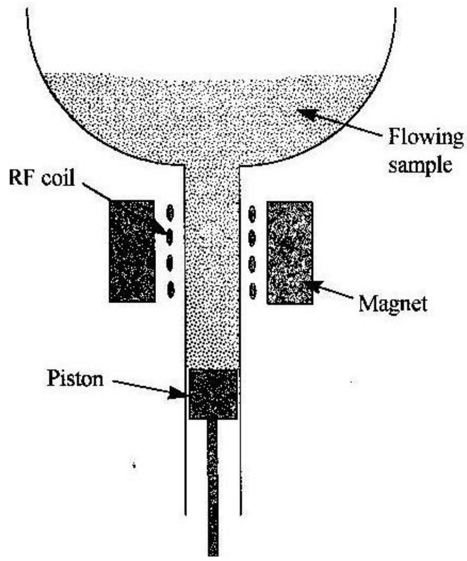

Fig V: Piston off-line sampling arrangement

B. Spatially Resolved On-Line NMR

The internal defects in fruits and vegetables, such as bruises, diseases, sages of ripeness, and worm damage, can, at least in principle, be detected noninvasively in MRI from changes in some NMR parameters, such as signal intensities, relaxation times, or diffusion coefficient. And building on-line MRI sensors of fruits or vegetable quality suitable for use with a moving conveyor belt in an industrial factory is possible.

Pitting fruits such as cherries, plums and olives is an important industrial process, usually preferred by holding the fruits and pushing the pit out of the fruit with a mechanical plunger. It is, of course, important that any samples still containing pits are detected with as high efficiency as possible. An on-line imaging system for detecting pits in cherries has been described [44]. It involves taking one-dimensional projection images using a spin-echo imaging sequence. Here cherries are positioned in the groove of a moving belt and a sagittal slice is taken through the cherries, followed by transverse projection through the slice. And distinguishing the cherries with pits relies on the use of superconducting magnets equipped with slice selection facilities.

VII. Conclusion

This technology provides real time internal process control for the food industry. Previously most of the parameters were tested and monitored by sampling or lab testing. But now by Using MRI, the results of additional tests such as: chemical analysis, oil and moisture distribution, sugar level, Ph and physical analysis of structure, voids, thickness of filling and coating, are immediately tested within seconds on the production line. And we can monitor and optimize the quality parameters of the foods which are being processed and stored. The idea about the value of MRI technology and its application in a food industry is going to improve and maintain the quality in processing, testing, and optimizing the parameters. And the high cost of imaging facilities is another hindrance to the exploitation of MRI in a food industry.

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