# MICROWAVE PROCESSING OF MAPLE SAP

by

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# ABSTRACT

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Maple sap was successfully transformed into maple syrup and maple syrup products by evaporation of water by microwave heating. Pulsed power supply with duty cycles of 100%, 75% and 60% were used for the microwave application. The dielectric properties of maple syrup at different moisture contents during the process were determined at 25° C. The products obtained were of excellent quality and were comparable to the highest grade prescribed by the industry. Pulsed power supply was found to have better efficiency of heating, but it increased the total time required for the process. The total time was also found to be dependent on the initial mass of the load. The behavior of the dielectric properties of the maple syrup was found to be fairly linear with moisture content and were found to be in close agreement with an empirical model found in literature. Microwave heating seems to have an enormous potential for production of high quality maple syrup.

# RÉSUMÉ

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La sève d'érable a été transformée avec succès en sirop et produits de l'érable en utilisant les micro-ondes. Les ondes du magnetron ont été appliquées aux produits par cycles de 100%, 75% et 60% du temps. Les propriétés diélectriques du sirop d'érable ont été determinées à 25°C. Les produits obtenus sont de qualité comparable aux standards de l'industrie. L'utilisation de l'émetteur d'ondes par cycles a donné de meilleurs résultats que son utilisation continuelle, mais augmente sensiblement le temps d'évaporation. Le temps total d'évaporation est dépendant du volume intitial de sève ou de sirop. Le comportement des propriétés diélectriques du sirop d'érable et de son taux d'humidité apparaît linéaire et suit les modéles empiriques trouvés dans la littérature. L'évaporation de la sève d'érable par micro-ondes semble promettre une production de sirop et de produits de l'érable de haute qualité.

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# FORMAT OF THE THESIS

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The work reported here was performed by the candidate and supervised by Dr. G.S.V. Raghavan, Professor and Chair, Department of Agricultural and Biosystems Engineering, Macdonald Campus of McGill University, Montréal, who is also the co-author for the manuscripts presented in chapters three and four.

# CHAPTER ONE

## 1. GENERAL INTRODUCTION

### 1.1 Introduction

The Maple is a tree of national importance to Canada, not only for its sentimental but also for its economical value. It is harvested for its hard, resilient wood and is cultivated for its sap, from which a natural syrup is obtained (Houston et al., 1989). This sap, which is mainly a dilute solution of sugars, forms the raw material for the production of the maple syrup, from which, many products are prepared. The collection of maple sap, followed by its transformation into syrup by boiling, is a very old custom inherited from the native American-Indians, who were the first to recognize it as a source of energy and nutrition. They used clay pots to boil maple sap over wood fires, to evaporate the water and obtain sugar. This custom was picked up by the French settlers and soon it became an integral part of the colony life, and during the 17th and 18th centuries, maple syrup was a major source of high quality pure sugar.

With changing times, many developments have taken place in the maple sap industry. Both, equipment and processing methods, are being modernized, in all the different areas involved like collection of sap, storage, processing, evaporation etc. All these changes have reduced labor requirements and production costs for producing better grades of syrup that have a correspondingly greater value (Willits and Hills, 1976). Today, the modern flue-type evaporator uses flues or deep channels in the pans and firebox with arched hot gases between them. The branches have left for the sugar shack which is now linked to the grove with a complex pipeline and vacuum system to harvest the sap.

It is often said that making syrup is not an easy task and that it is an *art* ! The amount of fermentation in the sap, the pH of the boiling sap, the concentration of sugars or solids in the liquids, the time of heating or time to evaporate the water from the sap and the temperature of the boiling sap are some of the factors that need to be controlled to achieve good quality syrup.

The single most important aspect of maple sap processing is the evaporation of water. Water is a polar molecule where the electrical charges within the molecule are nonuniformly distributed in space. This dipolar nature of water is exploited in the dielectric heating processes. In the past 15 years, applications of dielectric heating to food products have been thoroughly experimented. Feasibilities of successful applications of microwave drying to many materials have been shown in the laboratory or pilot-plant scale and many of these benefits have been realized in the processing industry. The unique heat and mass transfer mechanism involved in dielectric heating offers a number of potential advantages over convection and conduction heating; advantages such as reduction in time and energy input (UIE Working Group, 1988). The selectivity of the heating of water in presence of other materials present in the food qualifies the dielectric heating as a good means of drying and concentration of foods. There is an enormous potential for application of microwave heating in agriculture. Drying of agricultural commodities, seed treatment, insect control in stored grain and product processing are some of the different areas in which the technology is applicable (Nelson, 1985, 1987). Drying of corn using microwave heating has been studied by Hall (1963) at 2.45 GHz and by Fanslow and Saul (1971) who worked with 0.915 and 2.45 GHz. They found that the rate of drying of corn was much higher in case of microwaves than heating using the conventional methods. Gardner and Butler (1981) reported successful drying of rice and soybeans by microwave heating under partial vacuum. Shivhare et al. (1991, 1992) studied microwave drying of seed-grade corn using surface-wave applicators. They reported that the total drying time can be substantially reduced by using microwave energy. Gunasekaran (1990) dried corn in a commercial microwave oven at power levels of 10 and 20 W/g and reported faster rate of drying with good product quality as judged by visual observations. In drying of agricultural materials and food products, the control of the internal temperature of the product is very important so as not to burn the product. The internal heat generated due to microwave energy absorption directly depends upon the moisture content which is progressively decreasing with time. The temperature rise as a result of internal heating also affects the dielectric properties (Tulasidas, 1994). Microwave vacuum dryers have been commercially implemented for the production of fruit juice concentrates, tea powder and enzymes. The utilization of microwave energy allows the drying process of these heat sensitive materials at low temperatures and the resulting products have excellent rehydration characteristics

Microwave heating and drying processes have been well established in various industrial applications and in many cases are replacing the less efficient, economic and convenient conventional methods. The two basic advantages of microwave heating are the speed of heating and the quality of the product during heating. The in-depth heating due to the penetration of microwave energy through the material, equivalent to a volumetric rather than a surface distribution of heat, is beneficial for rapid and efficient utilization of the heat source. Besides a high degree of flexibility and control over the process is possible with microwaves. Since the energy is dissipated directly in the product, heat losses are considerably lower than in the conventional drying methods. However, microwave heating may not be economical as the sole energy source for drying high moisture content products. It may be well suited for finish drying or drying of low moisture content materials, where the heat damage occurring in the conventional methods can be avoided.

A closer observation of the maple sap processing industry will help in identifying the areas that call for technological changes from different points of view i.e. economical and environmental. As of now, the industry is predominantly a farm activity with limited large scale commercial implications. Farmers with maple groves are continuing the older and traditional methods which involve use of wood and fossil fuels for energy. It may be argued that the use of dead wood or older trees of the grove for burning may be an economical way of using the available energy source on farm and this might be true if the practice is looked at as strictly a farm activity and not as a profit making industry. But this use of wood is not environment friendly and besides, much better applications of biomass are being developed to which the wood can be diverted in which the conversion of energy are more efficient and economical. Even otherwise, the partial substitution of wood as a fuel in some phases of evaporation of maple sap, like the finishing stages, when the heat transfer gets progressively less efficient, by an economical and more efficient source of heating would be welcome. In areas where the electrical energy is available at cheaper costs, as in Quebec and Ontario where there is abundant supply of hydro-power, the switch over to an alternate heating method using electricity would be convenient and economical.

One of the most important drawbacks of the conventional evaporation methods used for processing of maple sap is the difficulty in maintaining the quality of the syrup. Effective control and strict monitoring of the heating is required for achieving good quality syrup. During the final or finishing stages, burning of the product due to excess heating near the heating surface is common. This results in lowering of the quality of the syrup (grade) due to darkened color and changes in flavor (associated with sugar degradation and caramelization). It is extremely difficult to exercise a high degree of control over the heating process when the conventional methods are followed. A combination of factors like the rate of burning of wood or oil, the rate of flow of syrup in the pans and the depth of the syrup in the pans are required to be orchestrated to end up with high quality syrup. The selective heating feature of microwave energy at this stage, for finish drying of the product, would be perhaps beneficial. As mentioned before, in regions where the electrical power is available at lower costs, the capital investment would be the only hurdle to tackle. However, the benefits because of the improved product quality, when translated to the additional revenue generated would be significant to cover this initial investment.

## 1.2 Objectives

The study was started with the broad objective of examining the potential of microwaves for application in processing of maple sap to produce maple syrup and further on, products from the maple syrup.

To supplement this general objective, the following specific objectives were set.

1. To evaluate the potential of microwave heating of maple sap for the production of maple syrup and maple syrup products.

2. To measure the dielectric properties of maple syrup at various stages of concentration.

3. To evaluate the quality of the maple syrup and syrup products obtained by microwave processing and compare it with commercial graded products.

# CHAPTER TWO

## 2. REVIEW OF LITERATURE

### 2.1 Introduction

Maple syrup is produced from the sap obtained by tapping the maple tree. The sap is basically a dilute solution of sucrose of 2 to 3° Brix (2-3%). It is concentrated by removal of water to prepare the maple-sap syrup (as opposed to the maple-sugar syrup which is obtained by dissolving the maple sugar in water) which has a sugar content of about 66%. The concentration is carried out usually in evaporating pans or kettles, with wood fire, by burning No.2 Oil or steam being used as sources of heat. The maple syrup is futher concentrated to obtain products like maple cream, maple candy etc. Different types of evaporators are used by the farmers and the efficiencies of these systems vary, depending on the local conditions.

The production of maple syrup involves removal of moisture by evaporation from the sap. Any method that can achieve direct heating of the water so that the heat supplied to the sap is essentially used for temperature rise and evaporation, is the best one from the point of view of efficiency. It has been shown that higher moisture products can be heated better using microwaves as the dielectric properties of water render it susceptible to microwave heating more easily than other constituents. Thus internal heating of water would cause expansion of moisture outward from the product and diffusion of it to the dry atmosphere (Copson, 1975). Heating in this fashion could be more useful in processes, where use of heating surfaces tends to pose hurdles for obtaining a good quality product due to problems of localised over heating. Since microwave heating can be used to heat only the water component, the burning of the solids could be minimized to a large extent.

In this chapter, the various aspects of maple sap production, the traditional methods of evaporation used and the different features of microwave processing are reviewed.

## 2.2 Maple Sap

### 2.2.1 Production

In 1930, total world production of maple syrup was shared almost equally between Canada and the United States. Between 1930 and 1980, the U.S. production constantly declined and now represents less than 30% of the total world production. Canada's total maple crop production represents presently 70% of the total world production. The production of maple syrup by the USA and Canada between 1986 and 1994 is shown in Fig. 1.

Canada's production is all located in the Eastern part of the country. 90% of the total Canadian production is in the Province of Québec. The Province of Ontario is the only other major producer in Canada, representing 5% of the total Canadian production. (FPAQ-internet site D)

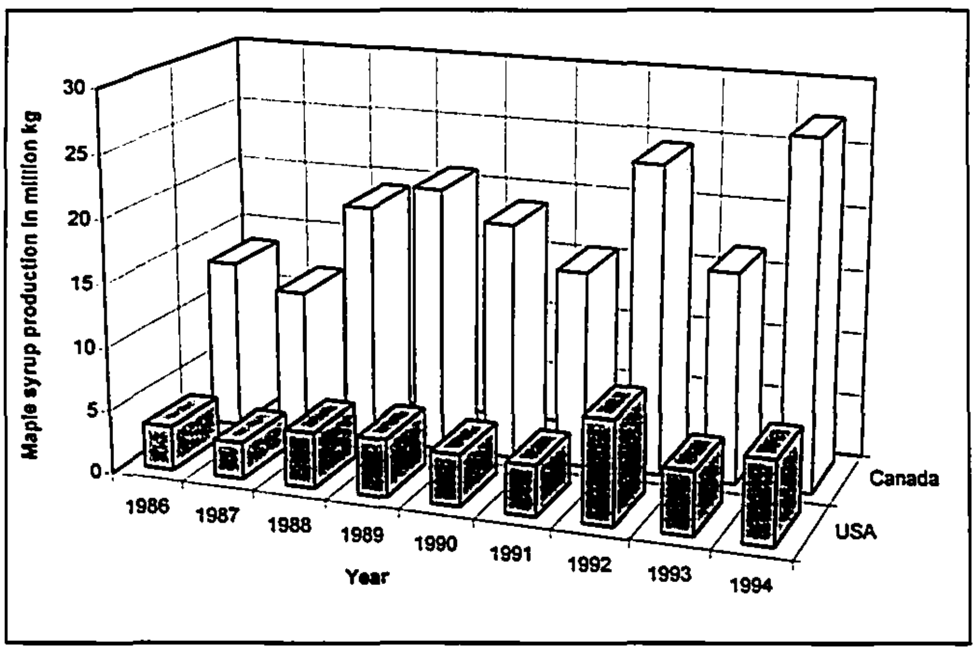


**Fig. 1. Maple Syrup Production in Canada and USA 1986-1994**
(Source : FPAQ - internet site D)

Of the many species of maple (*Acer*), only a few are important for syrup production. *Acer saccharum* Marsh. (better known as sugar maple, hard maple, rock maple, or sugar tree) furnishes three-fourths of all sap used in the production of maple syrup. It is most commonly found in the north-east USA and is best distinguished by its leaf (Fig. 2). *Acer nigrum* Michx. F. (black sugar maple, hard maple, or sugar maple) grows over a smaller range than does *A. saccharum*. It does not grow as far north and south but it is more abundant in the west. This tree is similar to *A. saccharum* in both sap production and appearance. Its principal distinguishing feature is the large drooping leaf of midsummer (Encyclopaedia Brittanica-internet site B). *A. rubrum* (Red Maple) and *A. saccharum* (Sugar Maple) are native to Québec and are widely used for production of syrup.

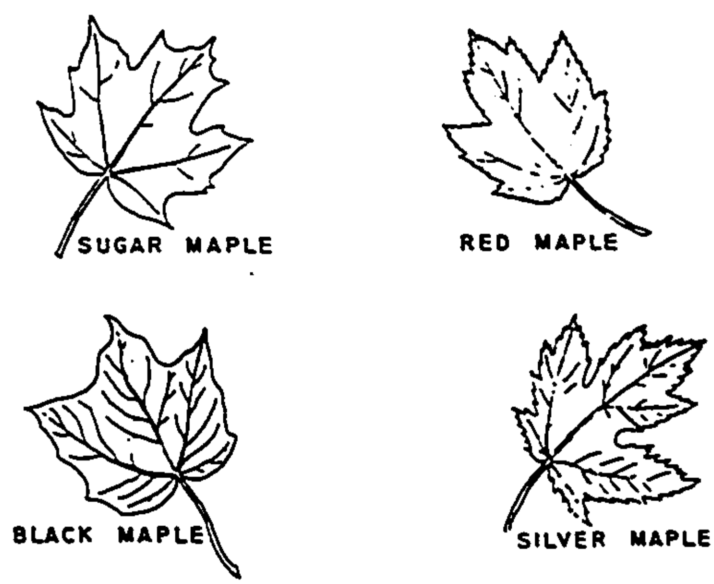


**Fig. 2. (clockwise) Leaves of sugar maple (Acer saccharum Marsh.), red maple (A. subrum L.), silver maple (A. saccharinum L.), and black maple (A. nigrum Michx. F.)**
**(Source : Willits and Hills, 1976 )**

The sap from the tree flows out of a wound in the sapwood, whether the wound is from a cut, a hole bored in the tree, or a broken twig. The sap is harvested by boring tapholes in the trees. While the traditional method was to collect the sap in buckets hung to the tapholes, modern methods involve a network of plastic pipelines, which enables convenient collection of sap from the point of produce to the point of collection thus reducing the microbial contamination and collection losses. The gradient required for the flow may be natural (gravity flow) or provided by means of vacuum pumps.

### 2.2.2 Sap composition

Table 1 shows the composition of maple sap. These are not average values: they are analyses of typical saps. Usually the syrup and sap have essentially the same composition, except that on an "as is" basis the constituents of the syrup show a thirty to fifty fold increase as a result of concentrating sap into syrup. The types of sugar in maple sap are not numerous. Sucrose, a disaccharide consisting of one molecule of Glucose and Fructose each and the same sugar as in cane sugar, comprises 96% of the dry matter of the sap and 99.95% of the total sugar in maple sap. The other 0.05% is composed of raffinose together with three oligosaccharides. Unfermented sap does not contain any simple or hexose sugar. However, it is possible for some degree of hydrolysis to occur during the collection and transport of the sap before it is evaporated, thus releasing some amount of hexose sugars. This is a factor that has significant bearing on the development of the flavor in the maple syrup. The degree of fermentation influences the sweetness, the formation of organic acids which participate in development of flavor compounds and to some extent the color of the finished product. The types of sugar occurring in maple sap and their percentage are given in table 2.

Table 1. Sap composition
(Source : Willits and Hills, 1976)

| Constituent | Percent |
|---|---|
| Water | 97.939 % |
| Sugars | 2 % |
| Organic Acids | 0.03 % |
| Minerals | 0.014 % |
| Proteins | 0.008 % |
| Others | 0.009 % |

Table 2. Sugars in maple sap
(Source : Willits and Hills, 1976)

| Sugars | wet basis % | Dry basis % |
|---|---|---|
| Sucrose | 1.44 | 99.93 |
| Raffinose and a glycosyl sucrose | 0.00021 | 0.014 |
| Oligosaccharides I | 0.00018 | 0.013 |
| Oligosaccharides II | 0.00020 | 0.014 |
| Oligosaccharides III | 0.00042 | 0.028 |

Typical values, not averages.

The oligosaccharides have been isolated by chromatography but not been identified.

## 2.3 Maple Syrup

### 2.3.1 Production of Maple Syrup

The preparation of maple sugar and syrup is strictly a farm industry, occurring from Kentucky northwest to Iowa northeast to Maine and north into Canada (Internet: netsite B).

Maple sap is transformed into maple syrup by evaporating about 66% of the water contained in the sap (which contains 97-98% water). About 25-42 litres of maple sap is required to produce one litre of maple syrup depending on its sugar content. This process is usually carried out in a sugarhouse or a sugar shack, where the sap is boiled in large pans to concentrate the solids. Many complex chemical reactions accompany this process of evaporation which produce the characteristic maple color and flavor (Internet: netsite D). Maple sap boils at 7.1° F (3.9° C) above the boiling point of water.

The sugar content of the sap produced by different trees in a grove varies considerably. The sap produced by the average tree has a sugar content of 2° to 3° Brix (Willits and Hills, 1976). Frequently, trees produce sap with a sugar content of less than 1° Brix and occasionally a tree produces sap with a sugar content of 9° or even 11° Brix. The finished product (maple syrup) will have a sugar content of 65.5-66° Brix (Internet: netsite B). The composition of the finished product is given in table 3.

**Table 3. Analysis of Maple syrup**
(Source: Woodman, 1941)

| Constituent | Maximum (percent) | Minimum (percent) | Average (percent) |
|---|---|---|---|
| **Water** | 48.14 | 24.85 | 34.22 |
| **Sucrose** | 70.46 | 47.20 | 62.57 |
| **Invert Sugar** | 11.01 | 0 | 1.47 |
| **Ash** | 1.06 | 0.46 | 0.66 |

### 2.3.2 Color and Flavor

The typical color and flavor of syrup are the result of chemical reactions, involving certain substances in the sap, brought about by heat as the sap boils. The browning reaction, giving the syrup its color, involves one or more of the six sugars. On the other hand, degradation of the syrup involves one or more of the 12 organic acids. The sweet taste of the syrup is attributed to the sucrose content in it and also to a small extent to the other sugars. It is quite usual for some fermentation to occur in the maple sap during the collection and the transportation to the evaporator. Depending on the extent of fermentation that has occurred in the sap, varying changes take place during the heating and evaporation. The pH of the sap rises during heating, leading to alkaline fission of the hexoses to form trioses which are chemically reactive and hence important for the development of the flavor and color. The substances resulting from the reaction of trioses with other constituents of the sap (like the organic acids) contribute to the typical maple syrup flavor. However, production of maple syrup with the typical flavor and color requires a strict control over the evaporation process. While the slight darkening of the color is correlated with the development of the flavor to some extent, it is important to control the heat damage to the product, especially at the finishing stages of the evaporation, as this could lead to the caramelization and other heat-induced changes, which reduce the quality of the syrup.

### 2.3.3 Classification

Maple syrup is classified according to color and taste, which can vary depending on the age of the maple tree and the presence of various organic and mineral elements in its sap. To grade different kinds of syrup, the industry uses the spectrophotometer equipped with optical cells which enable it to measure the exact percentage of light passing through the samples. The different Grades are classified as given in Table 4.

**Table 4. Classification (Grades)**
**(Source : FPAQ - (Internet site D)**

| | | |
|---|---|---|
| Canada No 1 | Very Clear | AA |
| Canada No 1 | Clear | A |
| Canada No 1 | Medium | B |
| Canada No 2 | Amber | C |
| Canada No 2 | Dark | D |

### 2.3.4 Characteristics of Maple syrup

Maple syrup has the following characteristics -

- 66° Brix at 20° C (68° F)
- Viscosity of 182 centipoise
- Density of 1.321 kg/litre at 20° C (231 $in^3$ at 68° F)
  (11.025 lb/gallon)
- Boiling point of 103.94° C at 101.325 kPa (at 760 mm of Mercury)
  (212 + 7.1° F)

## 2.4 Products from Maple Syrup.

Maple syrup is essentially a solution of sucrose in water, containing 67 % of sugar and is saturated at room temperature. To make any of the maple sugar products, it is necessary first to make supersaturated syrup. The degree of supersaturation is increased as the boiling temperature of the syrup is increased and more water is evaporated from the syrup. When the amount of supersaturation is small and cooling is slow and is accompanied by little or no agitation, the state of supersaturation may persist for a long time; and little sugar will be precipitated or crystallize out. When the amount of supersaturation is appreciable, as when syrup is boiled to 10° C, or more above the boiling point of water (6.1° C or more above that of standard density syrup), the syrup will appear to solidify on cooling. this solid cake is mostly sugar, but contains some liquid syrup (mother liquor).

The color and flavor of maple syrup result from a type of browning reaction that occurs between constituents of the maple sap during evaporation. However, to develop maximum flavor, the browning reaction must be carried further by heating the syrup to a higher temperature and for a longer time. However, this is not possible with all syrups as high temperature favours the formation of an acrid caramel flavor. Therefore, only the top grades of syrup can be used to make some products like the high flavored maple syrup. Because of the low moisture content of the syrup during the cooking period, there is danger of scorching if it is heated in a kettle on a stove or other hot surface.

### 2.4.1 Maple Sugar

Syrup that has been heated to raise the boiling point to 103.94° C or more will be supersaturated and when it cools to room temperature; it will contain more than 67% sugar. The excess sugar is forced out of solution and sugar crystals are formed. The crystalline or grainy nature of the precipitated sugar is determined by a number of factors, all of which are influential in making the desired type of confection. These factors include the degree of supersaturation, seeding, the rate of cooling and the amount and time of stirring.

Large crystals called rock candy, which represent one extreme, are formed when slightly supersaturated syrup (67-70° Brix) is cooled slowly and stored for a long time without agitation. A glasslike non-crystalline syrup represents the other extreme. This is formed when highly supersaturated syrup is cooled rapidly to well below room temperature without stirring. Other methods like stirring and seeding are also employed to achieve the desired crystal size.

### 2.4.2 Maple Cream

Maple cream, a fondant-type confection, is a spread of butter like consistency. It is made up of millions of microscopic sugar crystals inter spaced with a thin coating of saturated syrup (mother liquor). The crystals are impalpable to the tongue and give the cream a smooth, non gritty texture. The maple syrup in this case is first supersaturated by heating (112.2-113.3° C) and followed by rapid cooling to 10° C in order to prevent formation of large, perceptible sugar crystals. The cooled glass-like mass is then stirred, which produces the mechanical shock necessary to start crystallization. Fondant, a nougat-type candy, is made in exactly the same manner as maple cream except that the syrup is heated to a higher boiling point (115° C).

### 2.4.3 Soft Sugar Candies

The soft sugar candies are stiffer than maple cream, with sugar crystals big enough to be palpable to the tongue but without having any unpleasant sandy effect. In this case, the syrup is cooked to 117° C, cooled slowly to 68° C and then stirred. The sugar, while it is still soft and plastic, is poured into rubber molds of different shapes.

### 2.4.4 Maple Spread

The Maple Spread was developed as an improvisation over the maple cream, in which a tendency of the syrup (mother liquor) to separate out when stored at room temperature, was observed. The process for making the spread consists of concentration of the syrup to a density of 70° -78° Brix, by heating to about 105.5° C, and then cooling it to 65.5° C or less. This is followed by partial enzymatic hydrolysis of sucrose to invert sugar and the subsequent crystallization of dextrose to form a semisolid spread. The preparation of this product does not require any agitation and it is also more stable at room temperatures.

### 2.4.5 Rock Candy

Rock Candy is not considered as a typical product of maple syrup. It results from the prolonged crystallization of the sucrose to form large crystals, after the syrup has been heated to a density between 67.5 and 70° Brix. Similarly, the Hard sugar has been found to be a convenient form of storage of maple syrup, though it is not preferred as a confection. In this case, the syrup is heated to approximately 122.2° to 125° C.

### 2.4.6 Granulated Sugar

In the manufacture of granulated sugar, the syrup is heated to between 122.2° and 125° C, as in making hard sugar. The hot, partly crystallized, thickened syrup is transferred from the kettle to a stirring trough, and it is stirred continuously until granulation is achieved.

### 2.4.7 Maple on Snow

The syrup is heated to a maximum of 113 to 125° C in making the maple on snow and the final temperature within this range depends on individual preference. As soon as the syrup reaches the desired temperature, it is poured immediately without stirring on snow or ice, to get a thin glassy, taffylike sheet of maply syrup.

Apart from these, there are other products of maple syrup like Fluffed Maple Product, High-Flavored Maple syrup, Crystalline Honey-Maple Spread etc. which vary only slightly from the above products with respect to the heating.

## 2.5 The Evaporator

The maple syrup evaporator is an open pan for boiling water from the sap. The first evaporator, used by the Indians, was a hollowed log in which water was evaporated from the sap by adding hot stones. The next evaporators were metal kettles used by the white settlers. Till this stage, evaporators were of the batch type. The subsequent improvement in evaporators was the use of multiple kettles, which were the forerunners of the continuous type of evaporators. This system consisted of a series of kettles into which the sap was transferred for heating at different levels of concentration. The process was completed in the last kettle where the product was evaporated to obtain the desired final moisture level. The multi-kettle method was a semicontinuous operation and resulted in an improvement in the quality of the product as the syrup was heated at different rates during the different stages of preparation.

The introduction of the flat-bottom pan and the enclosed firebox brought about a major change in the design of the evaporators. This design increased the heating surface and gave more efficient use of fuel. The partitioned pan was the next stage in the evolution and this was the forerunner of the flue-type evaporator.

The modern flue-type evaporator, the last major change in design, appeared around 1900. The 'flues' or deep channels in the pans, combined with a modified firebox, arched the hot gases between the flues, caused the hot gases and luminous flames to pass between the flues before escaping up the chimney. This design improved the fuel economy, rate of evaporation, and hence lowered the cost of production.The product quality improved due to the shortened evaporation time.

The flue-type evaporator, which operates under atmospheric pressure, consists basically of two sections: (a) The sap pan, in which the flues are located, and (b) the syrup pan. The sections are separated to facilitate their removal from the arch for cleaning and repair. The sap pan can be made with narrow, deep channels because the sap, while in this pan, is never concentrated enough to become viscous and flows readily. Use of narrow flues increases the heating surface and thereby increases the heat transfer. The syrup pan, often called the front pan, is usually located over the fire box. Concentration of the sap to syrup is completed in this pan. It has a flat bottom to facilitate cleaning and to permit evaporation of shallow layers of syrup without danger of burning.

The modern flue-type evaporators include also a finishing pan after the evaporation section. This is to facilitate the slow drying of the viscous syrup during the final stages of evaporation. It is in fact a flat bottom pan, usually oil-fired, that continue the evaporation but at a much more slower rate, since it is imperative that the syrup comes to a 66-67° Brix level. At its best efficiency of about 75%, an oil fired evaporator can evaporate 20.5 kg of sap per hour to standard density syrup (Willits and Hills, 1976).

### 2.5.1 The Steam Evaporator

The evaporation of maple sap with high-pressure steam is practiced by a few producers. This has however not caught on much with the industry, though it has many advantages over the flue type evaporators. The heat is supplied in steam coils, manifolds or a jacketed kettle using steam.

A combination of steam and oil is proving successful in the recent times. In this two-stage system, oil is used to concentrate the sap to about 30° or 40° Brix in flue pans, and steam is used to complete the evaporation.

### 2.5.2 The Vacuum Evaporator

The use of evaporators operating under vacuum, as it is used in milk and fruit-juice concentration, was tried out for production of maple syrup (Baggley and Machwart, 1947). The sap was concentrated initially in a conventional open-pan evaporator at the farm site. The evaporation was completed in a vacuum evaporator at the central syrup finishing plant. However this involved the transportation of the semi-finished sap to the plant where the equipment was situated.

### 2.5.3 Fuel used

There are mainly two types of fuel used by the maple industry: wood and oil. Numerous types of wood can be used, but usually producers tend to use essences of wood that are normally found on the field. The energy content of typical wood commonly used in Maple Syrup preparation are given in table 5.

**Table 5. Typical calorific value of certain wood**
(Source : Willits and Hills, 1976)

| Wood | Btu/kg | KiloJoules/kg |
|---|---|---|
| **Maple** | 22 800 | 24 054 |
| **Beech** | 20 900 | 22 049 |

When wood is not used as a fuel, no.2 oil is normally used. One US gallon (3.785 litres) of no.2 oil gives 139,000 btu (146,645 kiloJoules) (Willits and Hills, 1976).

## 2.6 Theoretical aspects of Concentration of Sap

It is observed that the time taken to evaporate the water from the sap increases as the concentration increases. The solids concentration of the sap is about doubled before it leaves the sap pan (the first pan in the multi-stage evaporator) which means about 50% of the water that is to be removed has been evaporated. By the time the sap reaches a concentration of only 19° Brix, 90% of this water is evaporated (Willits and Hills, 1976). The changes in the concentration of a typical sap (2.5° Brix) during the evaporation in a conventional evaporator are given in table 6. The method of concentrating the sap in the conventional pans involves conductive heat transfer taking place from the heating medium to the heating surface and then convective transfer within the sap itself. In this case, the efficiency and the uniformity of heating is affected by various factors like the design of the evaporator, the fuel used, the viscosity of the sap at various stages, its turbulence while flowing through the pan etc. In practice, the producers carefully control the flow rate of the sap/syrup in the pans, their depth and stirring. Good stirring is necessary for effective convective heat transfer in the fluid which is also achieved by the use of baffles in some designs. Automated control of the depth of the fluid and the flow rate are also used.

**Fig. 3. Top view of a simulated maple sap evaporator having 3 channels in the sap pan and 4 channels in the sirup pan. Arrows shows direction of sap flow. The solid circles show the location of sap of different solids concentrations (° Brix) as indicated in the table 6.**

(Source : Willits and Hills, 1976)

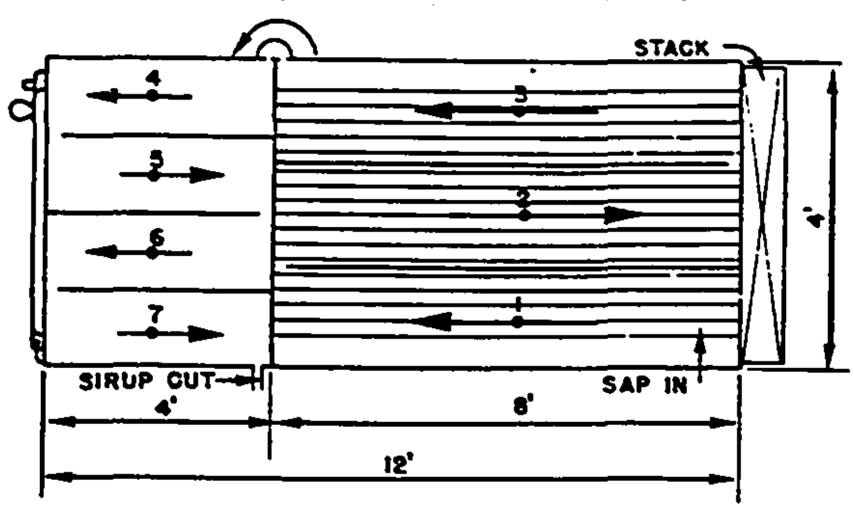

**Table 6. Changes in the brix value and water content of sap in a simulated evaporator, for each gallon of syrup produced.**
(Source: Willits and Hills, 1976)

| Section of the evaporator | Solids concentration of sap in °Brix | Water Evaporated | |
|---|---|---|---|
| | | Gallons | Percent |
| **Original sap** | 2.5 | | |
| **Sap Pan:** | | | |
| **First Section** | 3.0 | 5.77 | 17.35 |
| **Second Section** | 3.7 | 11.17 | 33.59 |
| | 5.0 | 17.33 | 52.12 |
| **Syrup Pan:** | | | |
| **Fourth Section** | 8.0 | 23.78 | 71.52 |
| **Fifth Section** | 19.0 | 30.04 | 90.35 |
| **Sixth Section** | 42.0 | 32.52 | 97.81 |
| **Seventh Section** | 54.0 | 32.97 | 99.16 |
| **Finished syrup** | 65.5 | 32.25 | 100.00 |

These factors are the major ones that directly influence the final product quality in terms of color and flavor. Due to the nature of the heating involved, the possibility of burning of the solids in the sap at the heating surface is always high. Hence effective arrangements to avoid localized over-heating are necessary to enable production of good quality syrup. Due to this problem, the heating at the final or the finishing stages should be gradual or slow so as to bring about equal distribution of heat throughout the fluid. This is a major drawback not only due to the increased processing time, but also in practice, it is difficult to control the rate of heating when wood is used as a source of heat.

### 2.6.1 The Brix Scale

The one specification that all grades of table maple syrup must meet, irrespective of color or other considerations is density. The minimum allowable density of maple syrup is 66% solids (w/w). Determining the density of the syrup by measurement of its refractive index which changes in a regular manner with changes in the amount of dissolved solids, is the simplest of the methods used to measure the density of syrup.

The Brix scale relates the density of the maple syrup to sugar solutions of the same density and known percentages of sugar. The Brix value of a solution indicates the percentage of sugar in solution that would result in that optical density. But since maple sap/syrup is almost entirely composed of sugar it can be conveniently used as the indicator of the dissolved solids content in that solution. Since the solids concentration of sap is comparatively low, its brix value and percentage of solids (w/v) are essentially the same.

## 2.7 Microwaves

Microwaves are the coherent and polarized electromagnetic waves with a frequency range from 300 MHz to 300 Ghz (Appendix 1). In the electromagnetic spectrum, the microwave frequency range lies between the radio waves and the infra-red regions.

Microwaves have many applications which include their use for telecommunication. Due to this reason, only certain frequencies are allowed to be used in Industrial, Scientific and Medical applications (ISM frequencies) (Appendix 2). Inspite of their high potential, the industrial use of microwaves for heating has been negligible compared to its application in domestic use in the form of microwave oven.

### 2.7.1 Microwave power generator

Microwave systems generally operate at a nominal frequency of 915 or 2450 MHz. The frequency is controlled by the tube dimensions and geometry. The generator consists of a DC power supply and a magnetron (cross-filed tubes) or a klystron (linear beam tubes). These tubes are constant output power devices, and power to the load must be controlled, usually by regulating the input power by indirectly varying the DC anode voltage (Decareau and Peterson, 1986).

The magnetron is a self-excited microwave oscillator. It consists of a resonant copper cavity made up of vanes and straps and is tuned to the desired frequency, and a thermionic cathode operating at around 1600° C and immersed in a magnetic field supplied by permanent magnets. An electrical field, produced by a voltage of several kilovolts, causes a space-charge of electrons emitted from the cathode, that revolve around the cathode and drift to the anode (vanes). The energy is converted to microwaves in the resonant cavity. The energy is stored in the cavity which supplies an output of microwave power from of a copper output antenna (Fig. 3). The klystron is a linear beam amplifier. A beam of electrons is generated by an electron gun made of a cathode and an accelerating anode. The electrons travel through a series of resonant cavities which are separated by sections called drift tubes and eventually impinge on the collector where they dissipate their residual kinetic energy. Electrons are focused into a narrow beam by the surrounding electromagnets. Once the microwave is generated, it is transported to the applicator by means of waveguides. Waveguides are metallic tubes with circular or rectangular cross-sections. The applicator is that component of a microwave system that couples energy with the product. A wide variety of applicators are available for various types of processes.

## 2.8 Dielectric Materials

Dielectric materials exhibit the property of polarisation because their molecular structure has strongly bound electrons unlike that of conductive materials which have free or loosely bound electrons. Under the influence of a rapidly alternating field, the realignment of the polarized components with that field gives rise to a friction effect within the material (UIE., 1988) As the electromagnetic wave travel through the material, the changes in wave polarity cause stress on ions, atoms and molecules, which is converted into heat. But the radiation is non-ionizing.

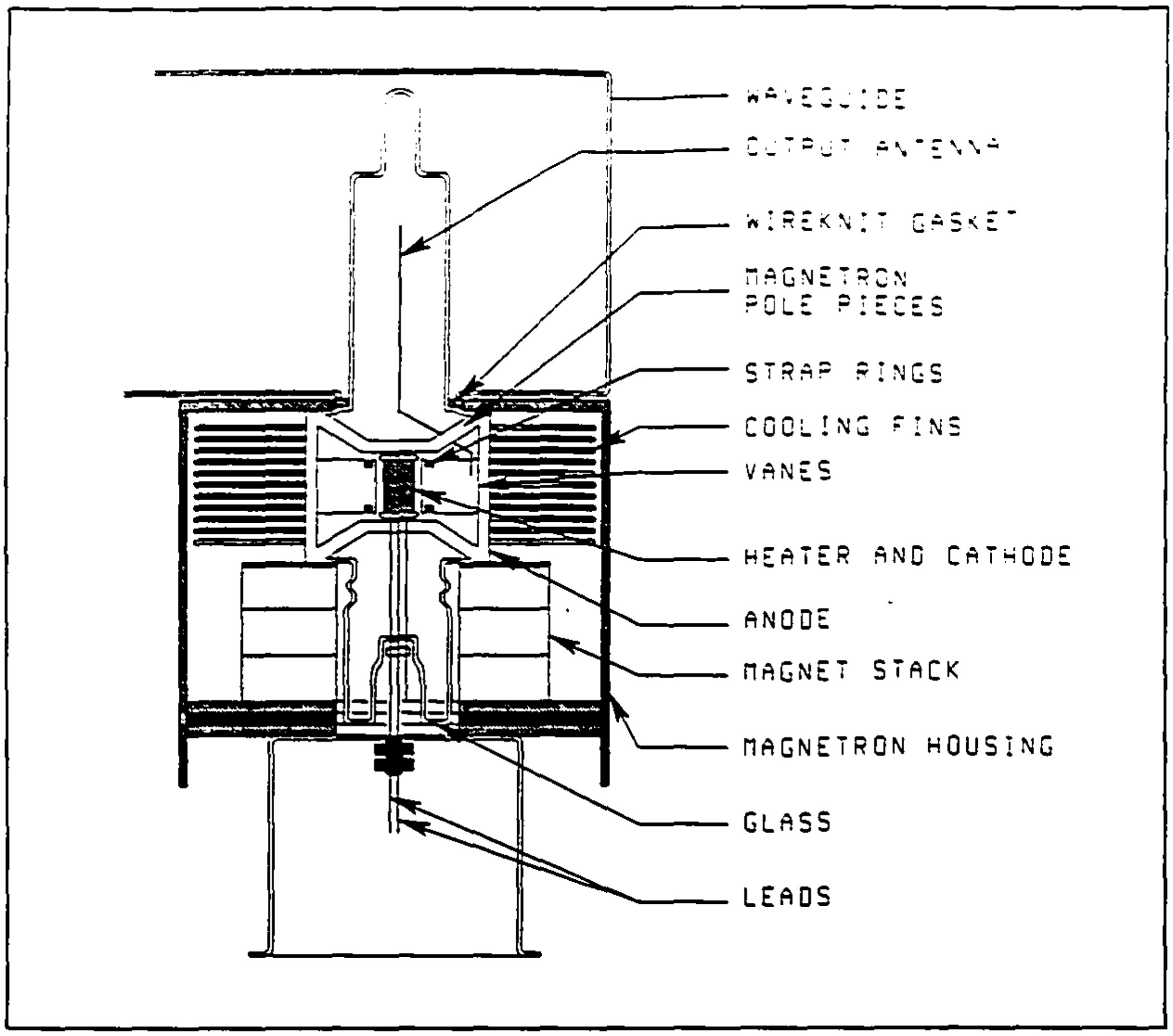


**Fig. 4 A typical magnetron for microwave oven**

### 2.8.1 Dielectric Properties

The energy transfer between the microwaves and the material exposed to the microwave field is influenced by the electrical properties of the material. The important dielectric properties are two dimensionless parameters - the relative dielectric constant ($\varepsilon'$) and the relative dielectric loss factor ($\varepsilon''$). The term 'relative' means that the value is relative to that of free space. The dielectric constant is a measure of the ability of a material to couple with microwaves or store electrical energy whereas the loss factor expresses the degree to which an externally applied electric field will be converted to heat (loss refers to the process of dissipation of electric energy within the dielectric material and implies the conversion of electric energy into heat) or the heatability of the material by microwaves (Decareau and Peterson, 1986; Buffler, 1993). In general the dielectric constant decreases both with increasing frequency and/or temperature. Although the loss tangent also changes with temperature, its behaviour with increasing frequency is less regular (Schiffmann, 1995). Their ratio, $\varepsilon''/\varepsilon'$, called the loss tangent, is a measure of the material's ability to generate heat. This factor, designated as $\tan\delta$, provides an indication of how well the material can be penetrated by an electrical field and how it dissipates electrical energy as heat. The third dielectric property which is closely associated with the other two and which is important for practical applications of dielectric heating is the concept of attenuation factor ($\alpha$). It is a measure of how the electromagnetic waves will be affected when they go from the surrounding air into the food medium. The attenuation of the penetrating microwaves will be directly proportional to the loss factor of the absorbing material and inversely proportional to the wavelength times the square root of the relative dielectric constant (Copson, 1975). This property is important for its association with the factor termed "Penetration Depth".

Even though microwave heating is termed as volumetric heating, in reality, the overall heating effect is a combination of volume and thermal conduction. The relative contribution of these heating processes is initially dependent upon the depth of penetration of the microwaves. The property of Penetration Depth has currently three definitions common in literature today. The Power Penetration Depth, defined as the depth at which the microwave power has decreased to 1/e or 36.8% of its original power (the original power refers to that power which has entered the sample, $P_o$, which is $P_i$, the incident power minus the reflected power $P_r$). This definition of penetration depth has gained international acceptance in the scientific community. The Electric Field Penetration Depth is defined as the depth at which the electric field has diminished to 1/e of its original value. It is equal to the inverse of the attenuation factor (Mudgett, 1986). This definition is commonly used by microwave engineers, but not predominantly used by food scientists. Another commonly used definition of penetration depth is the half-power penetration depth. It is simply the distance into a material that microwaves must penetrate before the microwave power is reduced to half its original value

The knowledge of dielectric properties and their relationship with composition of the commodity, the temperature and the frequency is essential for better understanding and analysis of microwave heating. Comprehensive reviews of dielectric properties at microwave frequencies for a wide variety of foods and agricultural products have been done by Bengtsson and Risman (1971), Nelson (1973, 1991), and Kent (1987). Ohlsson and Bengtsson (1975) studied dielectric properties of several foods at 450, 900 and 2800 MHz from 40 to 140° C. Water, the major constituent of most foods, influences the dielectric properties of these foods to a great extent. Most of the organic constituents of food are dielectrically inert, and compared to aqueous ionic fluids or water, may be considered transparent to microwaves . In high carbohydrate foods and syrups, the dissolved sugars (in water) are the main microwave susceptors. Hence, microwave heating is greatly affected by presence of water in foods (von Hippel, 1954, Nelson and Kraszewski, 1990). Dielectric properties of aqueous sugar solutions of different concentrations have been measured by Tulasidas et al. (1995)

The amount of free moisture in a substance greatly affects its high frequency heating as governed by its dielectric properties as water has a very high dielectric constant, approximately 78 at room temperature whereas the other constituents have dielectric constants of the order of 2. The water molecule possesses an electric dipole moment and is the primary component of a food that interacts with electromagnetic radiation at 2450 MHz. It has a very high loss factor and is particularly receptive to dielectric heating. This is of particular importance in drying applications. Water, with its high loss factor, can be easily removed from lower loss material. The host material with the lower loss factor will be relatively unaffected by the dielectric heating process, and as the water is progressively removed, due to changes in the dielectric properties, the electromagnetic energy is absorbed to a lesser extent by the host material.

### 2.8.2 Measurement of Dielectric Properties

Many techniques have been developed to measure the dielectric properties of agricultural and food materials (Nelson et al., 1994, von Hippel, 1954) and the measurements are performed by numerous methods employing various sizes and shapes. There are many reviews which discuss the principles and techniques of measuring the dielectric properties (Altschuler, 1963, Bussey, 1967, Franceschetti, 1967). The choices of measuring equipment and sample holder design depend upon the dielectric materials to be measured, the frequency or the frequency range of interest, the parameters on which the properties are dependent etc.

#### 2.8.2.1 Waveguide and Coaxial Transmission Line method

The early efforts to measure the dielectric properties of materials were associated with the transmission line theory, which indicated that the parameters, $\varepsilon'$ and $\varepsilon''$, could be determined by measuring the phase and amplitude of a reflected microwave signal from a sample of material placed against the end of a short-circuited transmission line, such as a waveguide or a coaxial line. For a waveguide structure, rectangular samples that fit the dimensions of the waveguide at the frequency being measured are required and for coaxial lines, an annular sample has to be used. The prerequisites demand that the sample preparation should be done keeping in mind the expected dielectric constant of the material being measured.

#### 2.8.2.2 Transmission line technique

The transmission line technique is considered cumbersome as the sample must be made into a slab or annular geometry. However, liquids and viscous material can be measured by employing this method by using a sample holder at the end of a vertical transmission line.

#### 2.8.2.3 Open ended Probe technique

This method was described by Stuchly and Stuchly (1980) and the technique calculates the dielectric parameters from the phase and amplitude of the reflected signal at the end of an open-ended coaxial line inserted into the sample to be measured. This technique is valid for 915 and 2450 MHz, for materials with loss factor greater than 1 (Marsland and Evans, 1987). Usually, the open-ended probes consist of 3.5 mm diameter coaxial line. This has been popular commercially and the compatible software and hardware required have been developed.

#### 2.8.2.4 Cavity Perturbation Technique

This technique is used frequently to measure the dielectric properties of food materials, especially of homogeneous food materials because of its simplicity, easy data reduction, accuracy and high temperature capability. It is most suitable for the accurate measurement of the dielectric properties of low-loss samples. This measurement utilizes the change in frequency and the change in absorption characteristics of a tuned resonant cavity. The advantage of such cavities is that the specific regions where energy is concentrated are known and the load is usually inserted into these regions where the field is at its maximum value. The decrease in the cavity's operating frequency and shift in the resonance frequency between that of the empty cavity and that of the cavity loaded with the sample, are used to calculate them (Akyel and Bosisio, 1990). The design of the waveguide cavity and the standard procedures have been published (ASTM, 1986).

### 2.8.3 Dielectric properties of Sugar Solutions

Maple sap is a dilute solution of sugars, containing about 2-3% sugars. There is no literature available regarding the dielectric properties of maple sap. However, the dielectric properties of sugar solutions of known strength have been studied. Tulasidas et al. (1995) compared the dielectric properties of sugar solutions and grapes at 2.45 GHz using the open-ended coaxial probe method. The dielectric properties of sugar solutions of different concentrations at 25° C are plotted against their corresponding water contents in Fig.4. As the concentration of sugar increased, the ε' was found to drop. Similar observations had been made by Roebuck et al., (1972) and Kudra et al. (1992) with respect to carbohydrates.

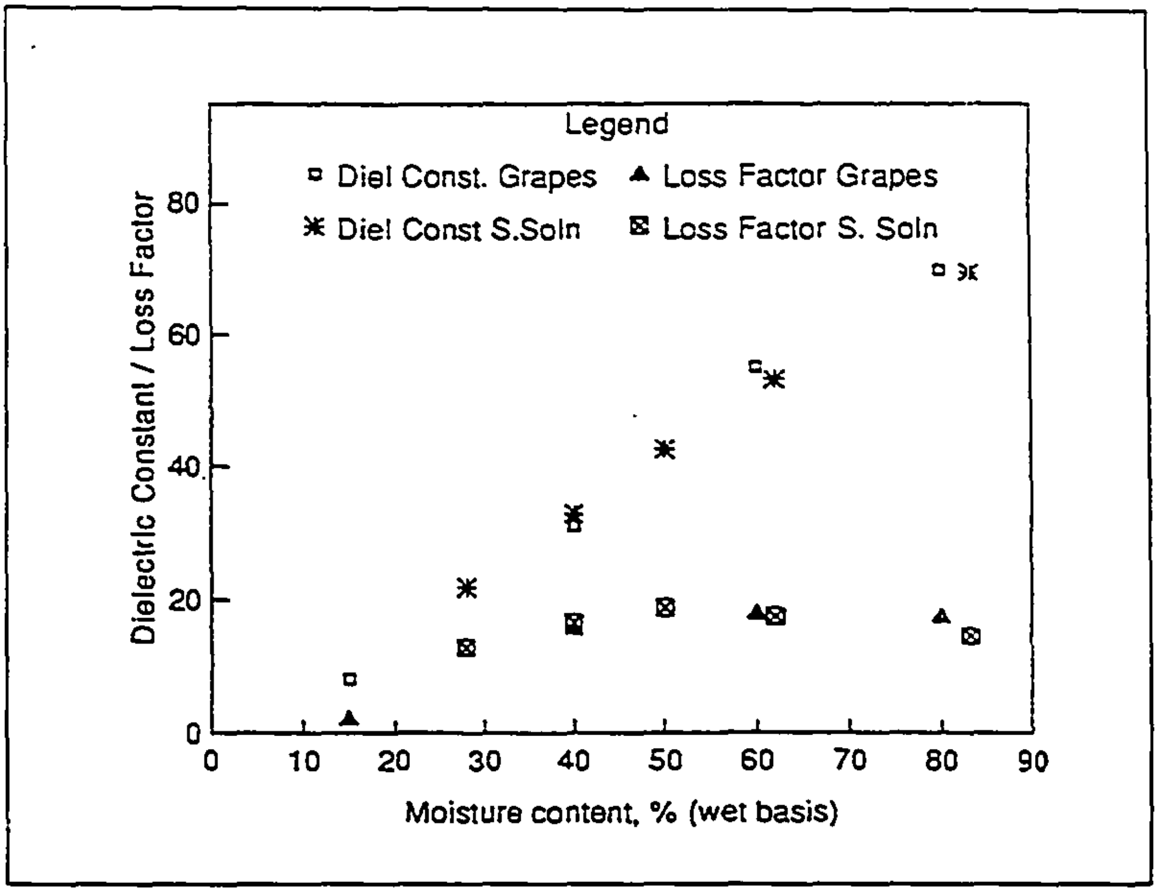


**Fig. 5 Dielectric properties of grapes and sugar solutions as a function of moisture content at 25°C and 2.45 GHz**
**(Source : Tulasidas et al., 1995)**

## 2.9 Microwave heating

Dielectric heating occurs due to two phenomena; the ionic conduction and the dipolar rotation. In the former, the ions are accelerated by the electric fields due to which, they collide with the un-ionized water molecules, giving up kinetic energy and causing them to accelerate and collide with other water molecules. When the polarity changes, as in an alternating current, the ions accelerate in the opposite direction. Since this is repeated many millions of times per second, large numbers of collisions and transfers of energy occur. There is a conversion of the electrical energy to induced kinetic energy which in turn is converted to disordered kinetic energy, at which point it may be regarded as heat. This type of heating is not dependent to any extent upon either temperature or frequency of the incident electromagnetic radiation. On the other hand, the dipolar rotation depends on the dielectric property of the water molecules which try to align themselves with the applied electric field as opposed to their normal random alignment. The degree of orientation of the molecules depends on the rate of orientation i.e. the frequency of the applied field, and the relaxation time, which is defined by the structure of the molecule, the viscosity of the solvent (the surrounding dipoles), temperature and the nature of the solute-solvent bonds. In this process, initially, the electrical field energy is converted to the stored potential energy in the material (in the oriented dipoles). As the polarity changes, this stored potential energy is converted to kinetic energy of the reorienting dipoles which interact with the surrounding molecules. During this interaction (mainly friction), there is a conversion of the energy to random kinetic or thermal energy, thus causing heating (Stuchly and Stuchly, 1983; Schiffmann, 1995). At microwave frequencies, dipolar rotation of water molecules usually dominates other heating mechanisms in the majority of materials.

Heating with the microwaves is a volumetric process in which the electromagnetic field interacts with the material as a whole and causes nearly an instantaneous heating. The heating occurs inside the food, without warming the surrounding air (Internet: site B).

Microwaves have three types of interaction with foods. They are reflected, transmitted or absorbed. The dissipation factor, tanδ, indicates how well the microwave field inside the food is converted to heat. The higher the value of tanδ, the more microwave energy will be converted to heat. As a result of dielectric loss, microwave absorption provides a volumetrically distributed heat source. The temperature distribution in a substance subjected to microwave radiation is thus governed by the interaction and absorption of radiation by the medium and the accompanying transport processes due to the dissipation of electrical energy into heat.

The volumetric power absorbtion by the material in the electromagnetic field is given by the relation

$$P = 2 \,.\, \Pi \,.\, f \,.\, E^2 \,.\, \varepsilon' \,.\, \tan\delta \qquad (1)$$

**P** = Power density in watts per cubic meter
**f** = Applied frequency in Hertz
**E** = Voltage gradient across the material in volts per meter (RMS-value)
$\varepsilon'$ = Dielectric constant of the material
**tan** $\delta$ = Loss tangent

The relationship between the loss factor and the moisture content can be utilized for achieving a self-limiting of heating in case of a microwave heated dehydration process. As water is removed, the dielectric loss decreases and hence, the material gets less heated. In conventional drying processes, moisture is removed initially from the external surface of the body producing the internal moisture gradient necessary for the outward diffusional moisture flow. As a result of the relatively dry surface, local overheating and structural damage of the materials are very common. Due to the nature of heating in microwaves, where the water is directly heated wherever and however it is dispersed within the body, the moisture content will decrease more uniformly throughout the bulk, evening out the moisture distribution (moisture profile) and thus eliminate the disadvantages of the conventional drying processes. Thus the temperature profiles resulting from microwave heating facilitate better moisture transfer and uniformity of drying, resulting in improved product quality.

# CHAPTER THREE

## 3. MICROWAVE PROCESSING OF MAPLE SAP TO MAPLE SYRUP AND MAPLE SYRUP PRODUCTS

### 3.1 Introduction

The Quebec maple syrup and maple products industry is in transition. The traditional maple syrup producer would cut and haul his own wood to fire open-pan evaporators; however, today's producers find themselves in the position of having less on-site wood to burn and less time to cut and haul. Many buy wood from others or have replaced their wood-fired furnaces by oil furnaces to supply heat for evaporation. The traditional open-pan evaporator is also being replaced by more efficient flue evaporators and by combinations of reverse osmosis and finishing evaporation driven by combustion. Since Quebec has ample hydroelectric power, one can envision the elimination of fossil or biomass fuels altogether. Changes in oil prices and market value of wood for other uses (lumber, home heating, etc.) could lead to a situation wherein electricity could become a source of energy for partial evaporation of maple sap to syrup. In particular, there is a possibility that electrical energy in the form of microwaves could be effective in the finishing of maple syrup and maple products. Since the heat transfer is radiative and does not involve heated container surfaces or elements in contact with the sugar solution, problems of scaling or overheating leading to undesirable color and flavor changes, could be avoided. A high quality of the finished syrups and other products (maple sugar, maple candy, maple butter, etc.) may be easier to achieve.

This paper describes preliminary experiments aimed at determining the potential of using microwaves to process maple sap. The objectives were to reduce sap to syrup and then to other maple products using microwaves alone, and to evaluate the quality of the maple products.

## 3.2 Materials and methods

### 3.2.1 Maple sap

All the sap samples used in the experiments were drawn from a single 45 gallon barrel from a St-Hilaire commercial sugarbush. It was distributed into smaller containers and stored under refrigeration until used for processing. The maple syrup obtained after microwave processing was used to further prepare the maple syrup products.

### 3.2.2 The experimental setup

A 750 W household microwave oven with variable controls was modified for this study and is shown schematically in Fig. 5. A weighing balance was fixed to the bottom of the oven so that the changes in sample mass could be monitored during the process. A second fan was also installed to ensure an adequate removal rate of the water vapor saturated air.

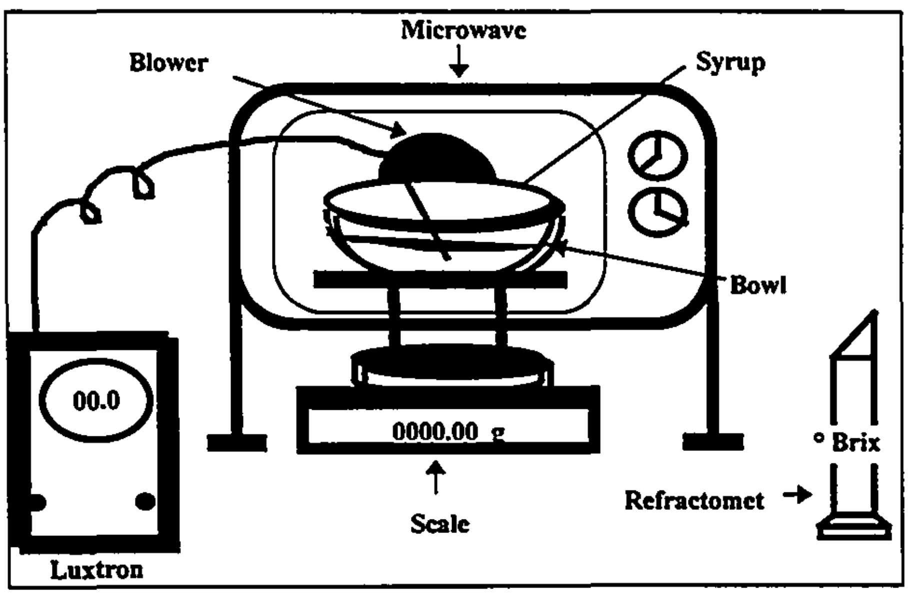


**Fig. 6 Schematic diagram of the experimental setup**

The instrumentation consisted of a 4-channel Luxtron 750 fluoroptic thermometry system, an A & D Company scale (Model EK-120A) and a Fisher hand-refractometer. A bowl was used to hold the sap sample. Microwave leaks were checked with a hand-held A.W. Sperry Microcheck dosimeter. A programmable timing controller from OMEGA was used to maintain the appropriate duty cycle of the microwave generator (on/off cycle).

### 3.2.3 Procedure

Three samples were prepared for each of three duty cycles, 100%, 75%, and 60%. Initial mass, sugar concentration (°Brix) and water content were determined. The mass, temperature and °Brix of the sap were measured at regular time intervals. The heating was stopped when the syrup attained a brix of 66°.

The following maple products were prepared from the syrup: maple butter, rock candy, maple on snow, maple spread, fondant and soft candy. These are generally prepared by heating the syrup and cooling in different ways to achieve the required consistency. The methods used in industry are listed in Table 7. In this study, heating was always done with microwaves, and cooling and stirring followed standard practice. About 500 ml of syrup were used for each run, and three trials were performed at each of two duty cycles (50% and 100%) for each type of product.

Table 7. Summary of the procedure followed to prepare Maple Syrup Products

| Product | Temperature to which syrup is heated or the change brought about in Brix | Cooling procedure |
|---|---|---|
| Maple Sugar | Heating to 103.94° C or till a brix of 67-70° is achieved | Slow cooling without agitation results in large crystals<br><br>Rapid cooling with seeding and stirring is required for formation of granular sugar |
| Maple Cream | Heating to a temperature of 112.2 to 113.3° C and 115° C in case of Fondant | Rapid cooling to 10° C followed by stirring or beating |
| Soft Sugar Candies | Heating the syrup to a temperature of 117° C | Slow cooling to 68° C followed by stirring and setting into moulds |
| Maple Spread | Concentration of syrup to 70-78° Brix by heating to about 105.5° C | Cooling to 65.5° C or less followed by partial enzymatic hydrolysis of sucrose to invert sugar and subsequent crystallization. |
| Rock Candy | Heating to approximately 122.2 to 125° C or till a brix of 67.5 - 70° is reached | Storing at room temperature with slow cooling till the sugar crystallizes out |
| Hard Sugar | Heating to 122.2 to 125° C | Stirring while hot with slow cooling until crystals are formed |
| Granulated Sugar | Heating to 122.2 to 125° C | Stirring after pouring it onto a tray or trough until granulation is completed |
| Maple on Snow | Heating the syrup to between 112 - 125° C | Pouring immediately on Snow or ice |

## 3.3 Results and discussion

### 3.3.1 Conversion of Maple Sap to Maple Syrup

#### 3.3.1.1 Moisture and Brix

The preliminary experiments on microwave boiling of maple sap to attain maple syrup resulted in syrups of good color and flavor; however, it was not possible to attain the same final Brix in all trials with the equipment available.

**Table 8. Initial mass, sugar concentration, sap temperature and time to reach 50° Brix.**

| Duty Cycle | Trial | In.Mass (kg) | In. Conc. (°Brix) | In.Temp (°C) | Time to Reach 50°Brix (min) | Rel. Time Use $kg^{-1}$ (min) |
|---|---|---|---|---|---|---|
| 100 | 1 | 1.224 | 2 | 6.4 | 88.3 | 72.1 |
| | 2 | 1.473 | 2 | 3.4 | 105.9 | 71.9 |
| | 3 | 1.546 | 3 | 4.8 | 113.3 | 73.3 |
| 75 | 1 | 1.475 | 2 | 5.0 | 134.2 | 68.2 |
| | 2 | 1.463 | 3 | 5.1 | 122.3 | 62.3 |
| | 3 | 1.568 | 2 | 9.1 | 136.3 | 65.2 |
| 60 | 1 | 1.535 | 2 | 6.8 | >140 | n/a |
| | 2 | 1.338 | 1 | 8.6 | 120 | 53.8 |
| | 3 | 1.237 | 2 | 14.5 | 105.5 | 51.2 |

The initial sugar concentrations, masses and temperatures are summarized in Table 8, along with the time taken to reach 50° Brix and a relative energy use for this time. The relative time use is calculated as the time taken to reach 50°Brix, multiplied by the fraction of time the magnetron is on (1.0, 0.75 or 0.60), and divided by the initial mass of the sap sample. For roughly equivalent initial mass, the time for concentrating the sap is dependent on the duty cycle - it takes less time to concentrate at higher duty cycles. However, the relationship is not linear with energy emitted by the magnetron and it is actually more energy efficient to work at a lower duty cycle, even though the time taken to concentrate the sap is longer.

The changes in sugar concentration with time for the full duration of each of the nine runs are shown in Figures 6 to 8. There is an initial period (20 to 30 min) during which the Brix value does not change noticeably and which corresponds to the initial increase of sap temperature to its boiling point (about 102°C). The next period shows a slow increase in Brix; however, it should be recognized that a doubling in Brix corresponds roughly to removal of half the water present at the lower Brix value. The sharp rise in Brix in the final short period is explained by the fact that very little water must be removed per unit change in °Brix when the solution is quite concentrated.

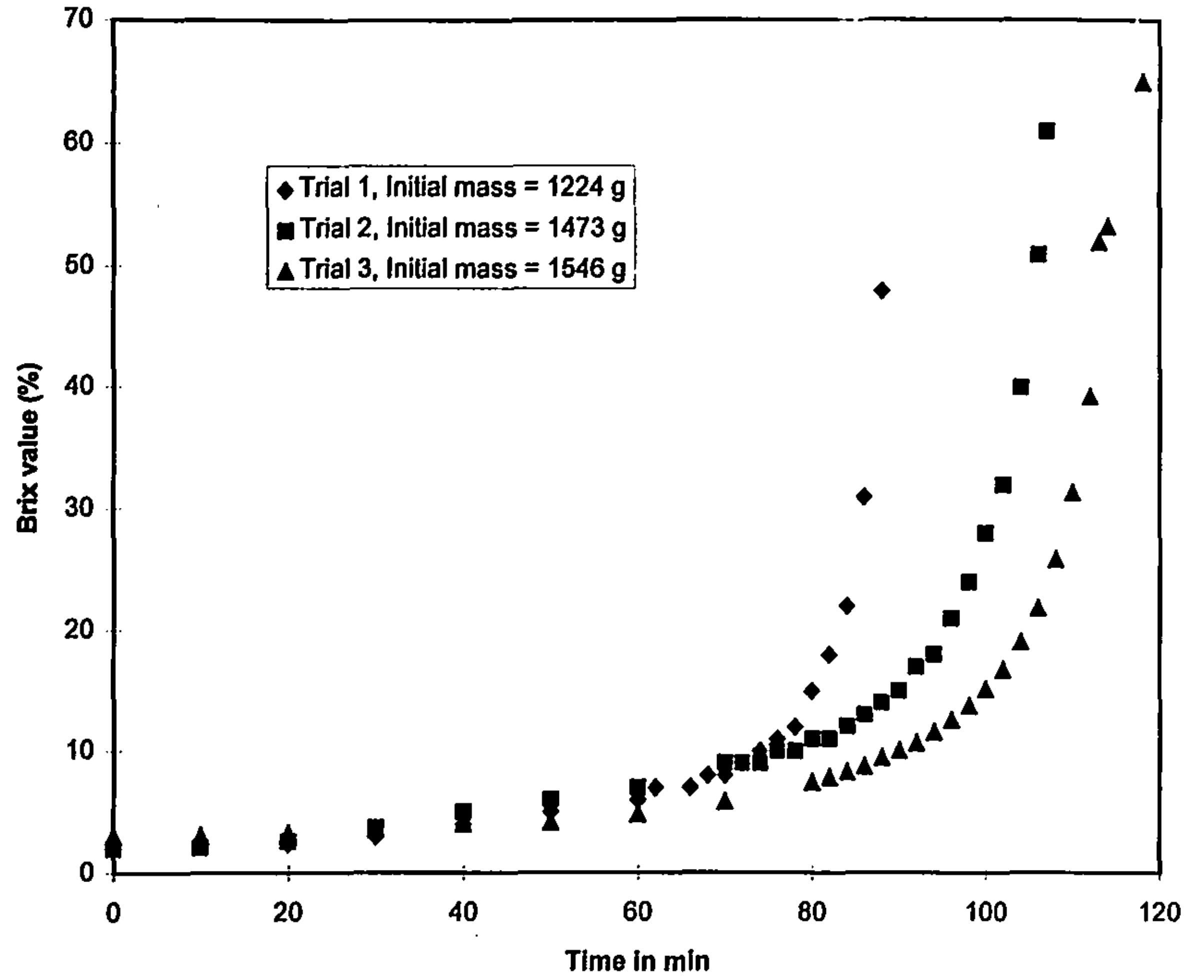


Fig. 7 Change in the brix value with time for 100% duty cycle

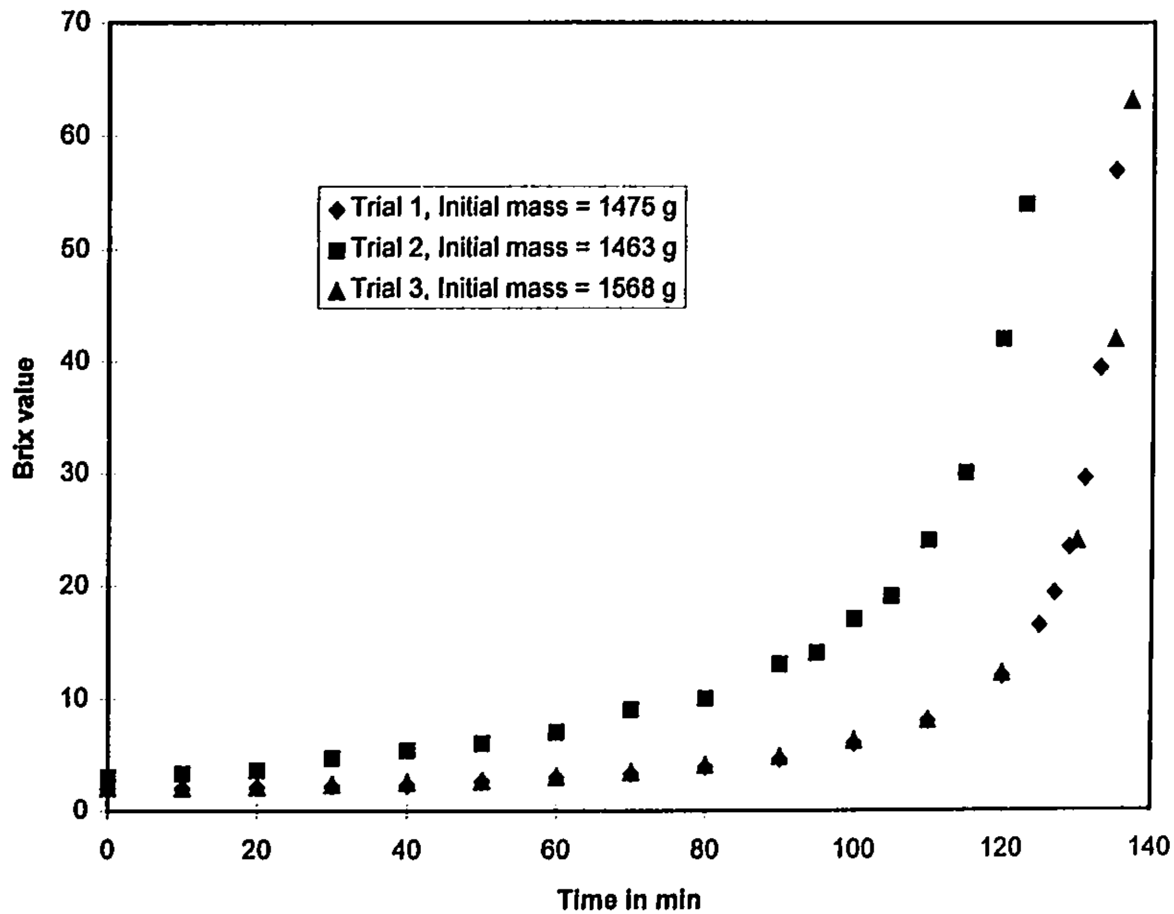


**Fig. 8** Change in the brix value with time for 75% duty cycle

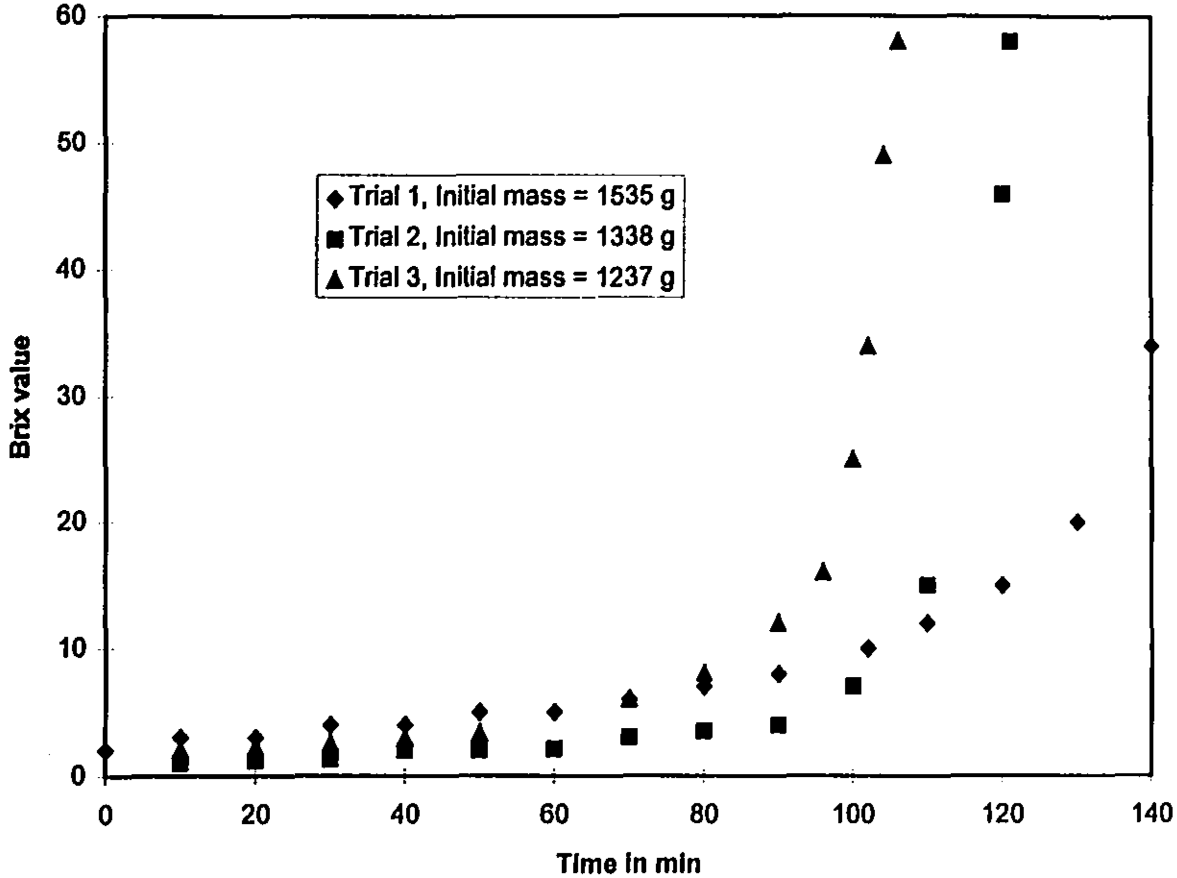


**Fig. 9** Change in the brix value with time for 60% duty cycle

The process of concentration of maple sap when visualised as a function of time (Fig. 6 to 8), exhibits a regular behaviour. The relationship between the Brix value of the maple sap and the time required for the process resembled the "Harris model" as described by the equation

$$y = \frac{1}{a + bx^{c}} \qquad (2)$$

where $y$ = Brix value of the maple sap/syrup at any given time $x$
$x$ = Time
a, b and c are coefficients.

a is the reciprocal of the initial brix of the maple sap. b and c are coefficients which are influenced by the physical process and are related to the physical parameters in the process like the initial mass of maple sap taken for processing and the rate of change of brix during the process. This relation fits the observed points quite well ($r^2$ = 0.83 to 0.88).

These data are perhaps better represented in terms of evaporation rate (Fig. 9), or unaccomplished moisture content (Figures 10 to 12), both of which are obtained from the readings of mass, adjusted for initial Brix (ie. estimate of solids content).

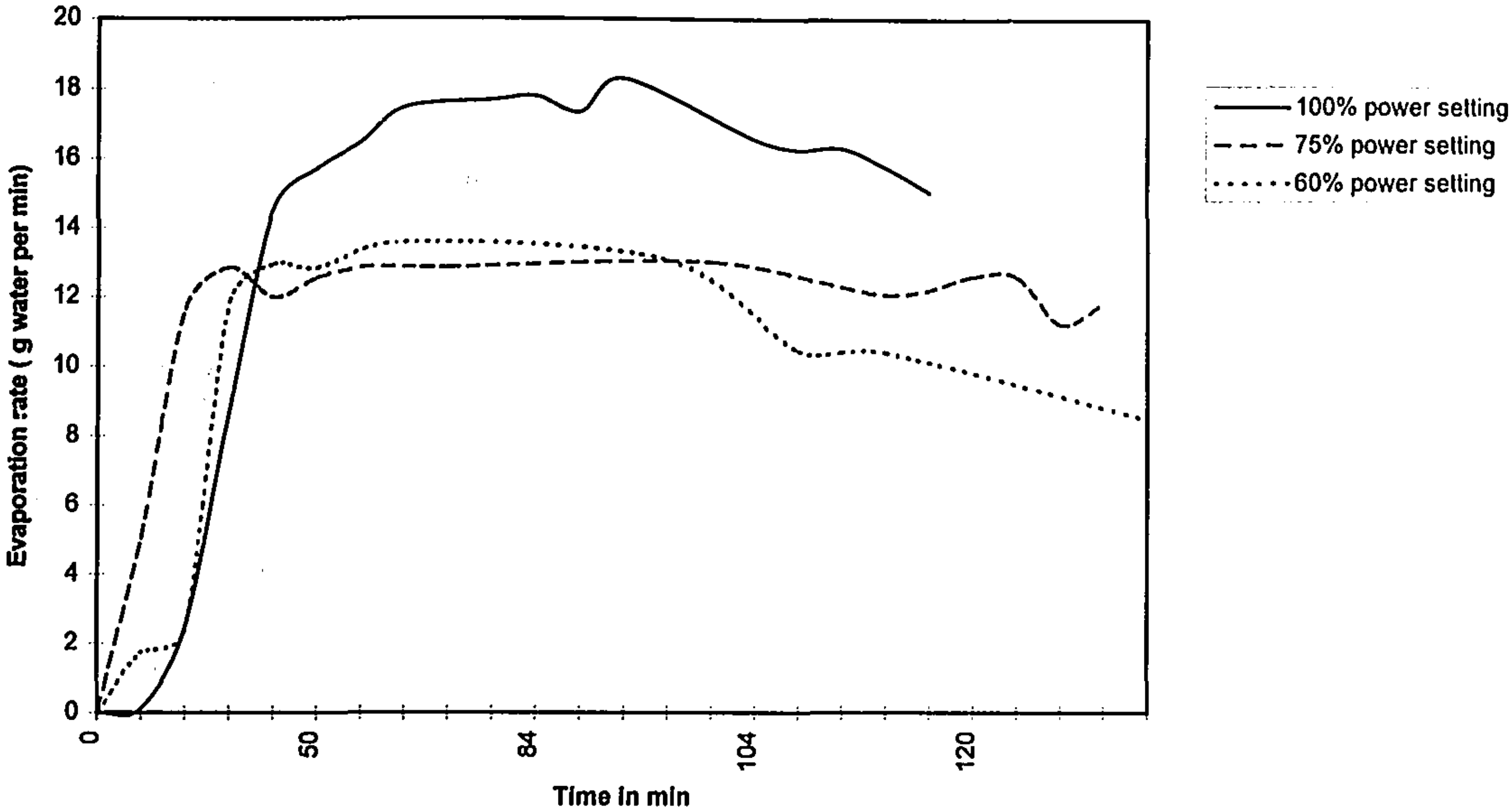


**Fig. 10** Comparison of evaporation rate in the three power settings

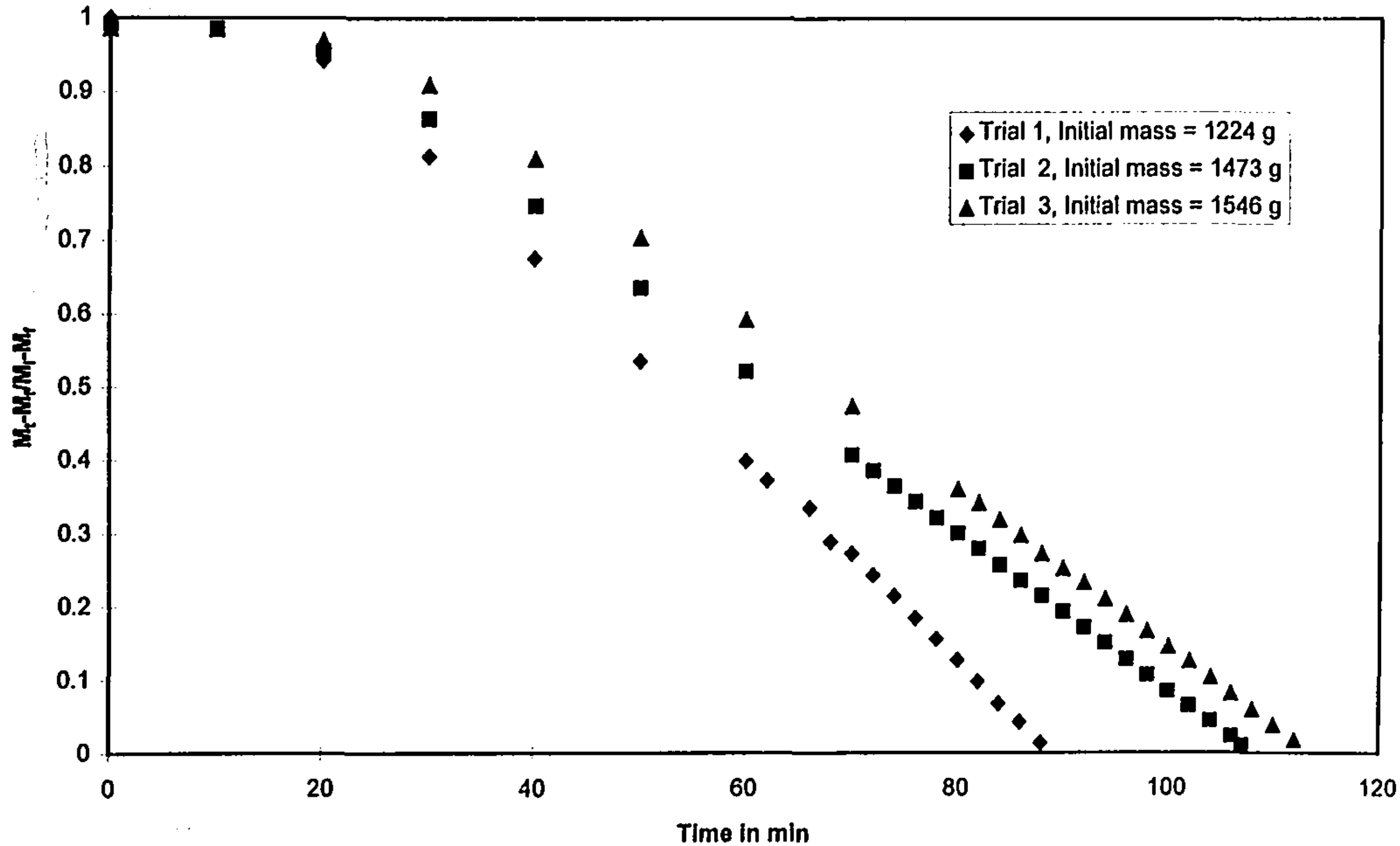


**Fig. 11** Unaccomplished moisture content as a function of time for 100% duty cycle

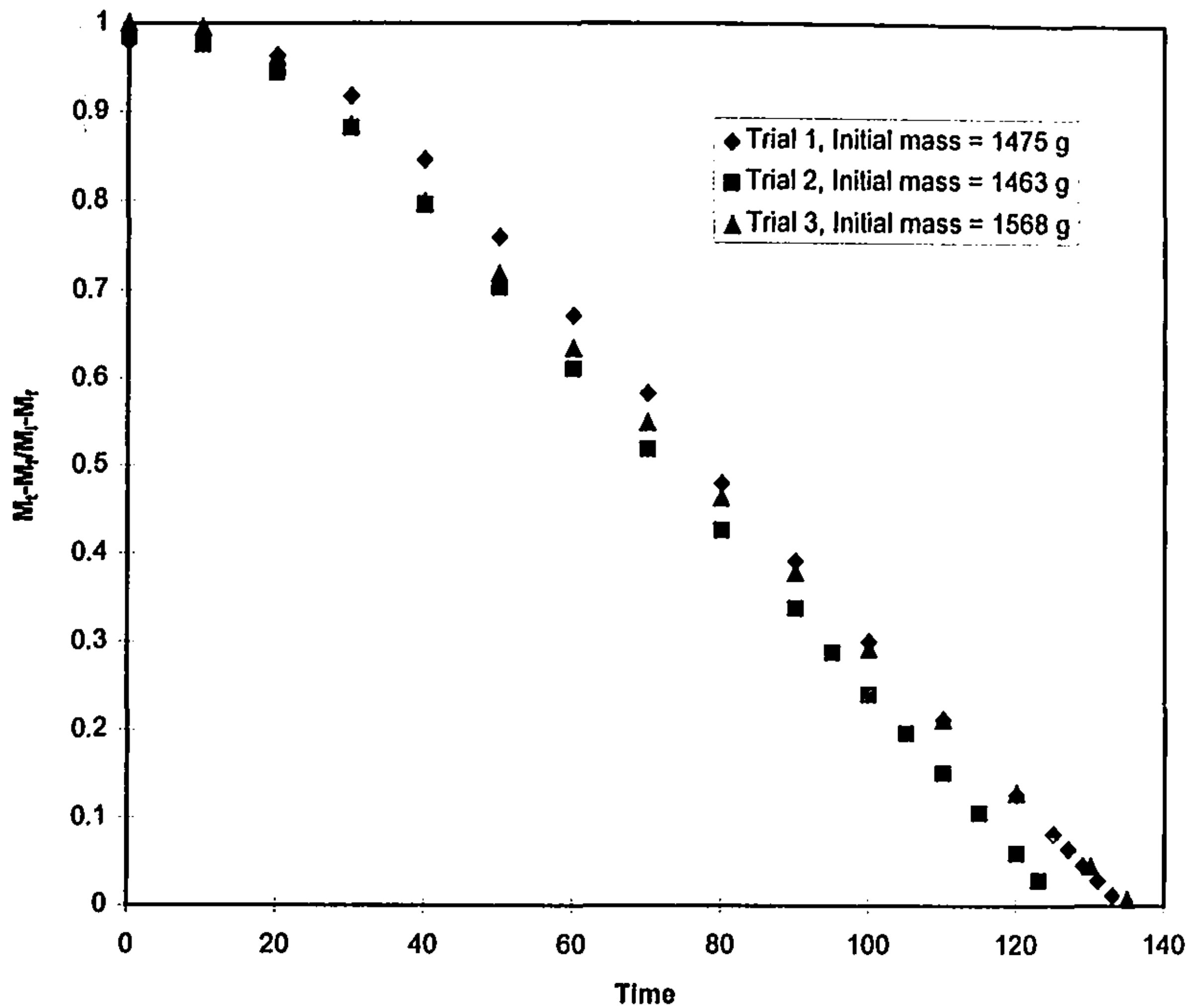


**Fig. 12** Unaccomplished moisture content as a function of time for 75% duty cycle

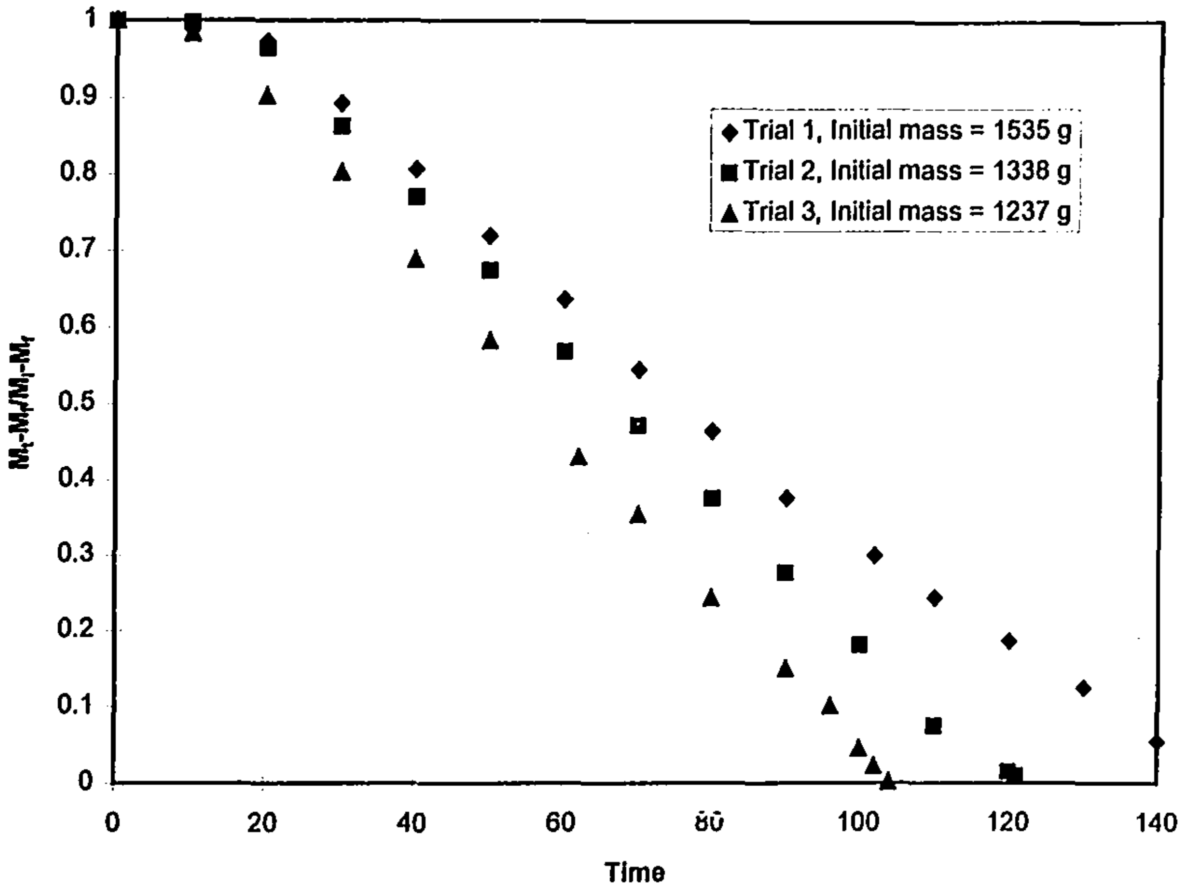


**Fig. 13** Unaccomplished moisture content as a function of time for 60% duty cycle

Unaccomplished moisture content is a useful indicator in food dehydration. It is similar to the well-known moisture ratio used in drying and defined by:

$$MR = (M_t - M_e) / (M_0 - M_e) \qquad (3)$$

where $M_t$ = Moisture content at any time t

$M_0$ = Initial moisture content

$M_e$ = Equilibrium moisture content.

but $M_e$ is replaced by the final or desired moisture content, $M_f$.

Thus, the unaccomplished moisture content is written as:

$$UMC = (M_t - M_f) / (M_i - M_f) \qquad (4)$$

which is the ratio of the amount of water yet to be removed at time t to the total quantity of water to be removed from the product. This form is more convenient in modeling applications to non-convective drying or water removal processes, since the equilibrium moisture content is often unknown or does not exist, as would be the case for contact drying on a very hot surface or in an intense microwave field, of a heat-labile substance. In the case of maple sap, caramelization and reactions leading to color or flavor changes could occur under such conditions.

Figures 9 to 12 indicate that there is initial period of little water removal, followed by a sharp rise indicating that the boiling temperature has been reached. Thereafter, the moisture removal rate is roughly constant and tapers off near the end of processing since very little water is left. There is no obvious relationship between the evaporation curves shown in Figures 9 to 12 and the duty cycles because the initial conditions (Table 8) are not the same. The initial mass of sap is particularly important because the time to reach the boiling point for a given duty cycle depends on it; for example, a smaller mass at 60% duty can reach the boiling point more rapidly than a larger mass at 100% duty.

Specific relationships between critical points in the Brix or evaporation curves and the microwave operating parameters could be worked out if a proper experimental methodology were used. Alternatively, quantification of the dielectric properties of the sap at different concentrations and temperatures could be used to describe the heating rates and to set up a model to describe and/or control the process.

#### 3.3.1.2 Power absorbed

The power absorbed by the load in the microwave oven and the efficiency of its utilization for removal of water is the governing factor when microwave processing is considered for evaporation. The power absorbed by the maple sap during the process was calculated based on the difference in temperature, the amount of water evaporated and the specific heat of the solution (calculated as a function of the total solids). The total power absorbed over a period of time represented the power required to raise the temperature of the load plus the power required for evaporation of water during that period.

The variation in power absorbed and the water content at different times of the process for the three power settings is shown in Figures 13, 14 and 15. The initial rise in the power absorbed is an artifact due to the method of calculation which does not account for the heat transfer from the sap to the container in the initial period. In other words, the sap heats up more slowly at the beginning because some of the energy is being used to heat the container. As the sap begins to boil and water is gradually evaporated, the power absorbed decreases in an almost linear fashion, corresponding to the decrease in load, or unaccomplished moisture content.

#### 3.3.1.3 Quality of the Maple Syrup

The quality of the maple syrup obtained in the study was assessed by comparing it with commercially available products. The color of the syrup prepared by microwave processing was found to be comparable to the Canada No.1 (AA grade) syrup. The flavor was typical of maple syrup with no burnt or "high" flavor. The consistency of the product was viscous with no burnt or charred particles and was very clear. No taste panel tests were done for judging the syrup.

### 3.3.2 Conversion of Maple syrup to syrup products

The conversion of maple syrup to syrup products mainly involves heating the maple syrup to different temperatures above the boiling point or further dehydration of the syrup to a certain level of brix and then cool the mass in different ways to achieve varying consistencies, as described earlier in Table 7.

Maple syrup products were prepared by heating the maple syrup in the microwave oven in less than thirty minute period followed by cooling in the manner required to obtain the characteristics of that particular product.

The power absorbed was calculated using the temperature difference, the specific heat and the brix content of the syrup at different stages. A comparison of the total power absorbed and the temperature as observed at different time intervals during the process are shown in Figures 16 and 17 for 100% and 50% power setting respectively. The total power absorbed increases initially to reach a peak and then it follows a gradual decrease. The initial increase is required for increasing the temperature of the load from the ambient to the boiling point and subsequently, the power is utilized for evaporation of water from the syrup and further increase the boiling point of the syrup. It can be observed that the maximum power absorbed is higher in case of the 100% power setting and also the time required to bring the sap to boil is less in that case. The increase in temperature or the boiling point of the sap is associated with an increase in the brix value.

#### 3.3.2.1 Quality of the Products

The quality of the maple syrup products obtained by microwave processing were evaluated by comparing with commercial graded samples. However no taste panel judgment was carried out. The products obtained were found to be of excellent quality; there were no indications of any undesired flavor or color.

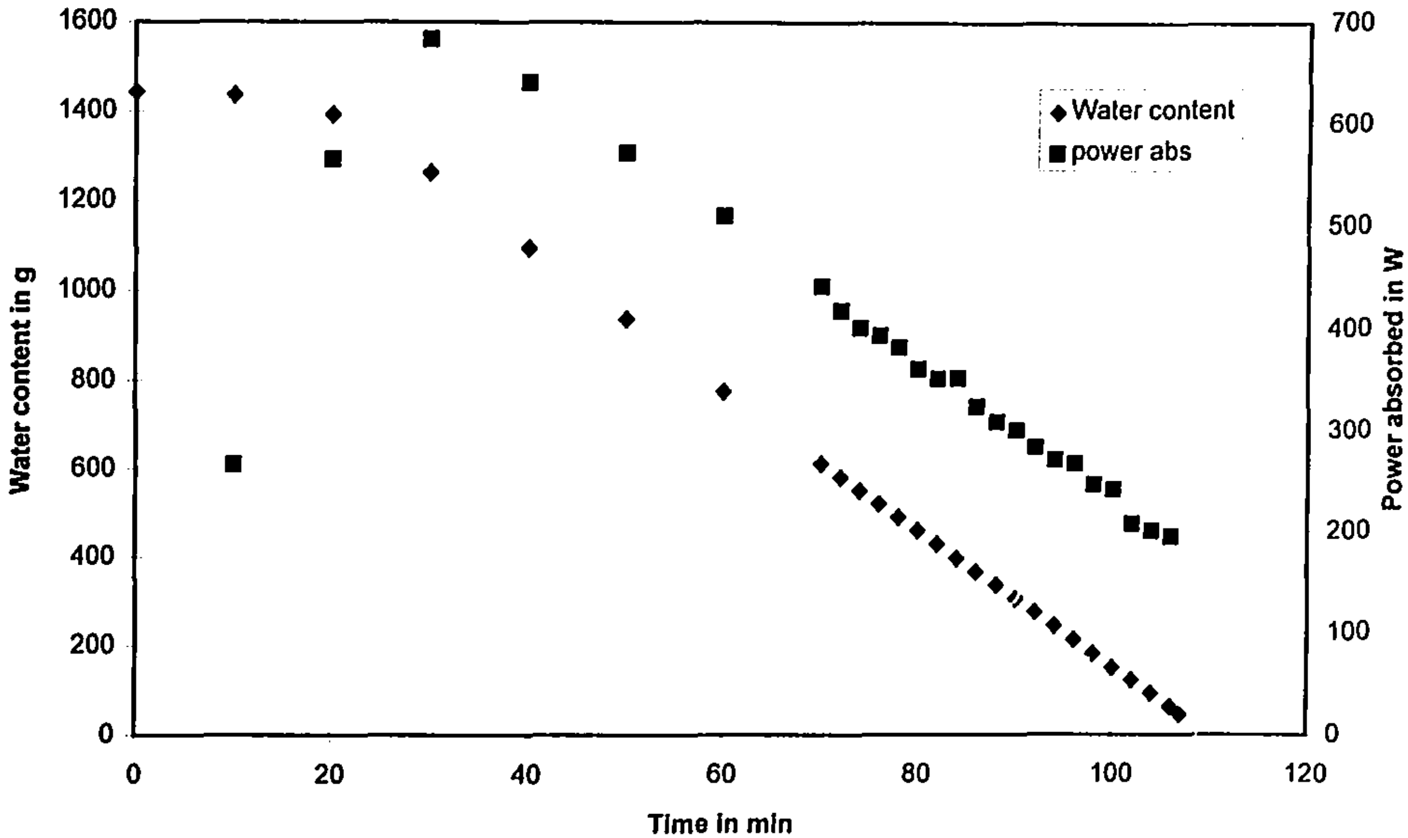


**Fig. 14** Comparison of change in water content and power absorbed with time for 100% duty cycle

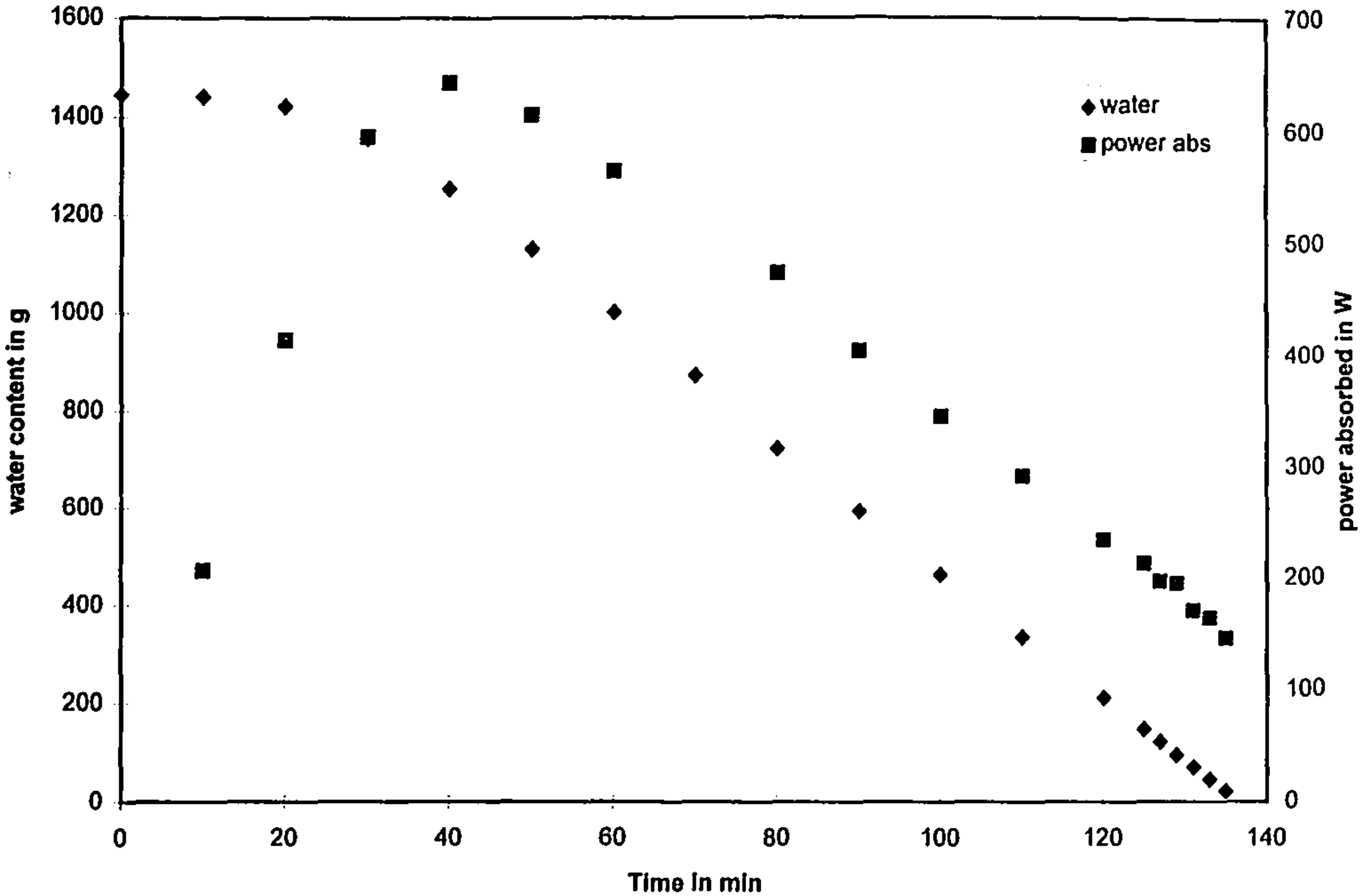


**Fig. 15** Comparison of change in water content and power absorbed with time in 75% duty cycle

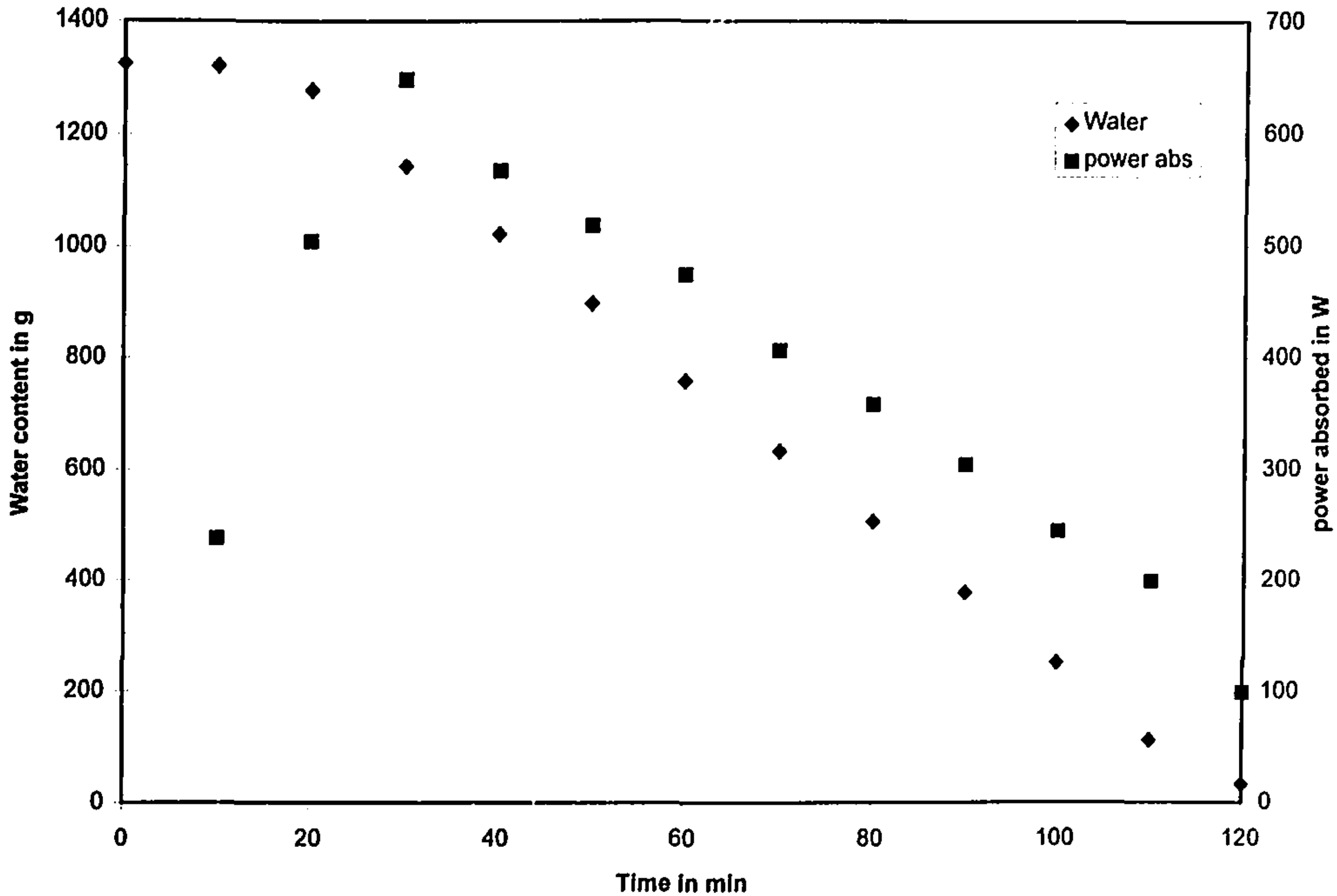

Fig. 16 Comparison of change in water content and power absorbed with time in 60% duty cycle

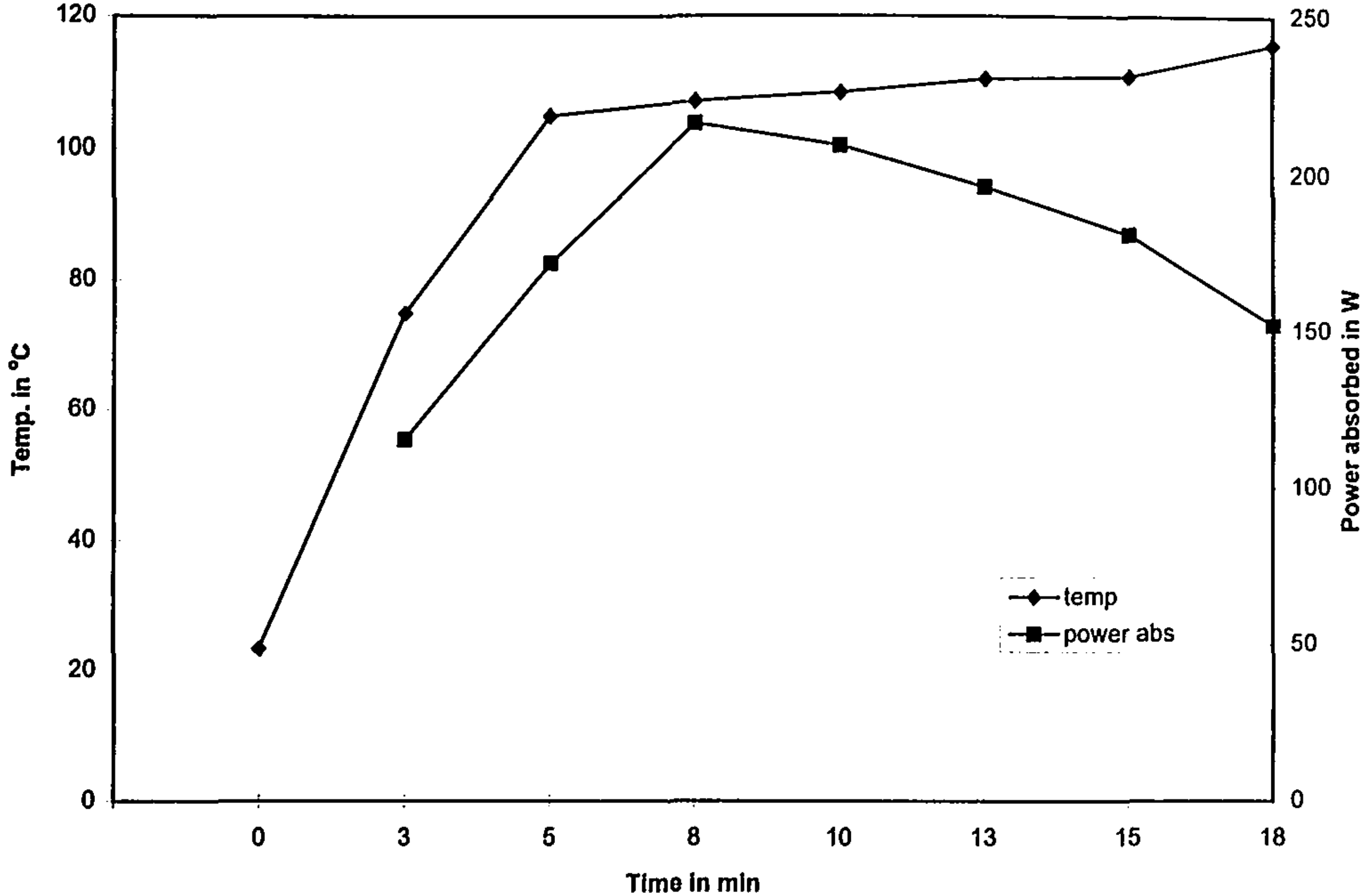


**Fig. 17** Comparison of the variation in temperature and power absorbed with time for 100% duty cycle

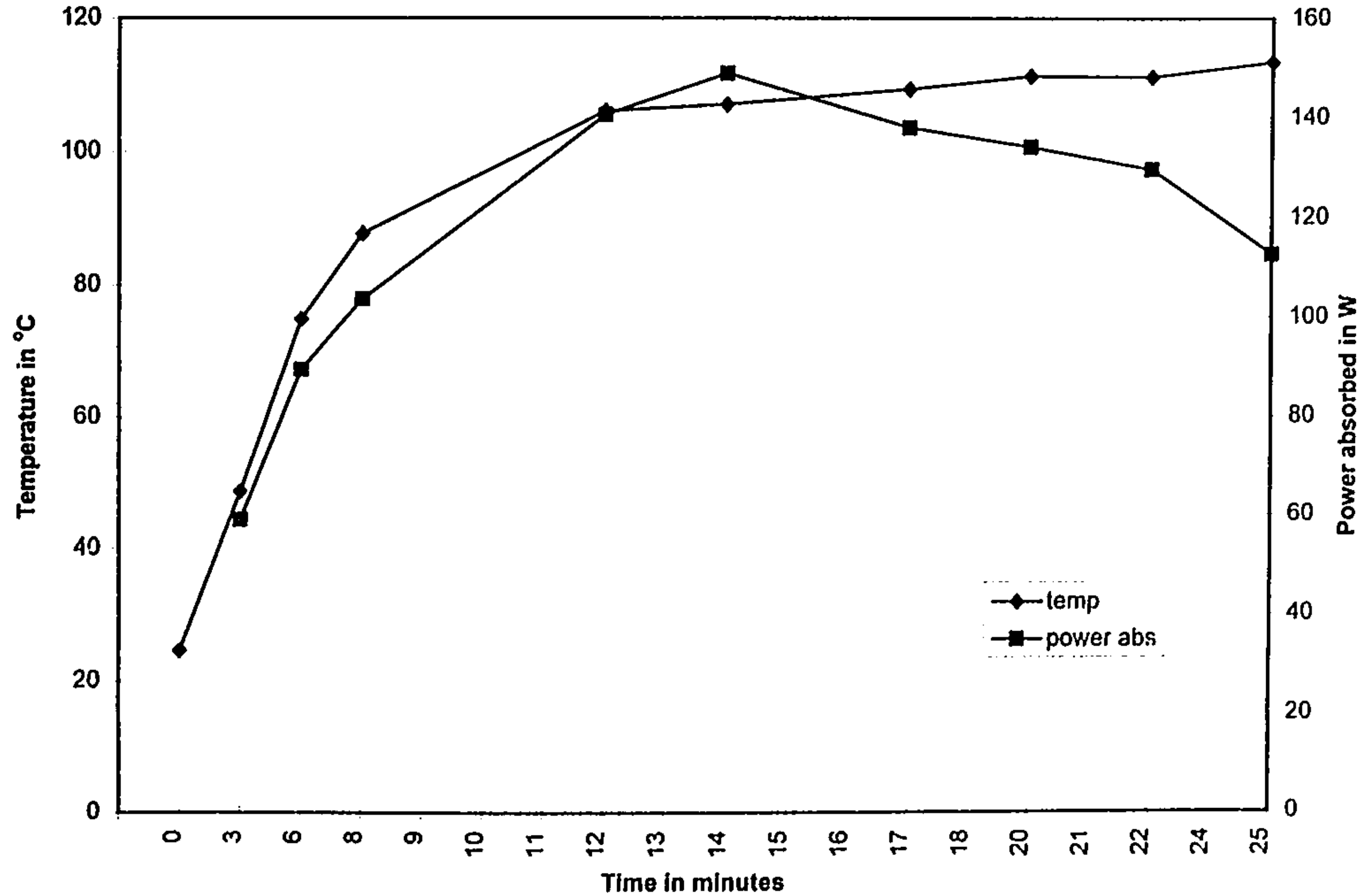


Fig. 18 Comparison of the variation in temperature and power absorbed with time for 50% duty cycle

## 3.4 Conclusion

Maple sap was successfully transformed into maple syrup and maple syrup products which were found to be of excellent quality when compared with commercial samples. Microwave processing promises to be a good technology for maple syrup making which has remained within the traditional folds for long. It can be integrated in the sugar bushes with other energy saving methods like Reverse Osmosis to enable production of maple syrup with lower processing costs. However, the kinetics of the concentration is required to be studied in depth to provide information regarding the energy utilization, the type of equipment and their scaling up, the compatibility of the technology with other methods for integration and continuous processing set-ups and also the possibility of having a single or variable microwave processing system for different agricultural products in a farm.

One of the areas which require greater study for assessing the potential of microwave processing of maple sap is the dielectric properties of maple sap/syrup. The results obtained in that direction during this study are discussed in the next chapter.

# CHAPTER FOUR

## 4. DIELECTRIC PROPERTIES OF MAPLE SAP AND SYRUP AT 2.45 GHz

### 4.1 Introduction

The study of the dielectric properties of agricultural products is important in the processing industry to determine the potential for using electromagnetic radiation for processing and also for subsequent interests like design and development of equipment for that purpose. These properties govern the nature of application and the extent to which it can be used economically. The important dielectric properties - the relative dielectric constant and the dielectric loss factor are needed for predicting various essential microwave processing parameters such as penetration depth, the attenuation factor, the power density etc.

The dielectric constants are functions of mainly the frequency and the moisture content of the product and to some extent, the temperature. Thus, in applications such as drying and concentration of liquids, these properties are time dependent. When a constant frequency is used for microwave heating, the moisture profile and the corresponding dielectric behavior data can be useful in evaluating the suitability of the process at different stages.

In keeping with the objectives of the study, the dielectric properties of the maple sap at different stages of processing it to syrup were determined. This was intended to study the relationship of the dielectric behavior of the product with the changes occurring during the processing. This data is useful in the overall analysis of the microwave processing of maple sap.

## 4.2 Materials and Methods

The maple sap was converted to maple syrup using the experimental setup described in chapter 3. The samples were drawn off at different intervals of time and the brix value and temperature were measured.

The dielectric properties were determined at 2450 MHz using an Open-ended Co-axial Probe system HP 85070B. Based on the phase and amplitude of the reflected signal at the interface between an open-ended co-axial line and the sample, the dielectric parameters were calculated using a custom-built software. The properties were determined by a Hewlett-Packard 8753 C Network analyzer/ 85047A, 300 KHz to 6.0 GHz S Parameter test set (Hewlett-Packard Corp., Santa Clara, CA). The setup was calibrated using a short circuit with mercury, air and pure water at room temperature and the calibration was verified by taking measurements of a standard liquid of known dielectric properties.

## 4.3 Results and Discussions

### 4.3.1 Dielectric constant

The dielectric constant of maple sap as a function of moisture content at ambient temperature (25 °C) is shown in Fig. 18. The curve represents the changes occurring in the dielectric properties during the processing of maple sap to maple syrup and is fitted to the experimental points visually. The observations were taken between the moisture contents of 98% and 35%, which correspond to that of the maple sap and the maple syrup respectively. Maple sap, with about 98% moisture, has $\varepsilon' = 78$. This progressively decreases and by the end of the processing, the dielectric constant of the maple syrup is about 32. The behavior seems to be mostly linear with moisture and a quadratic relation fits well (correlation coefficient = 0.999). The values for dielectric constant obtained in this study for maple sap/syrup are in close agreement with those available in literature.

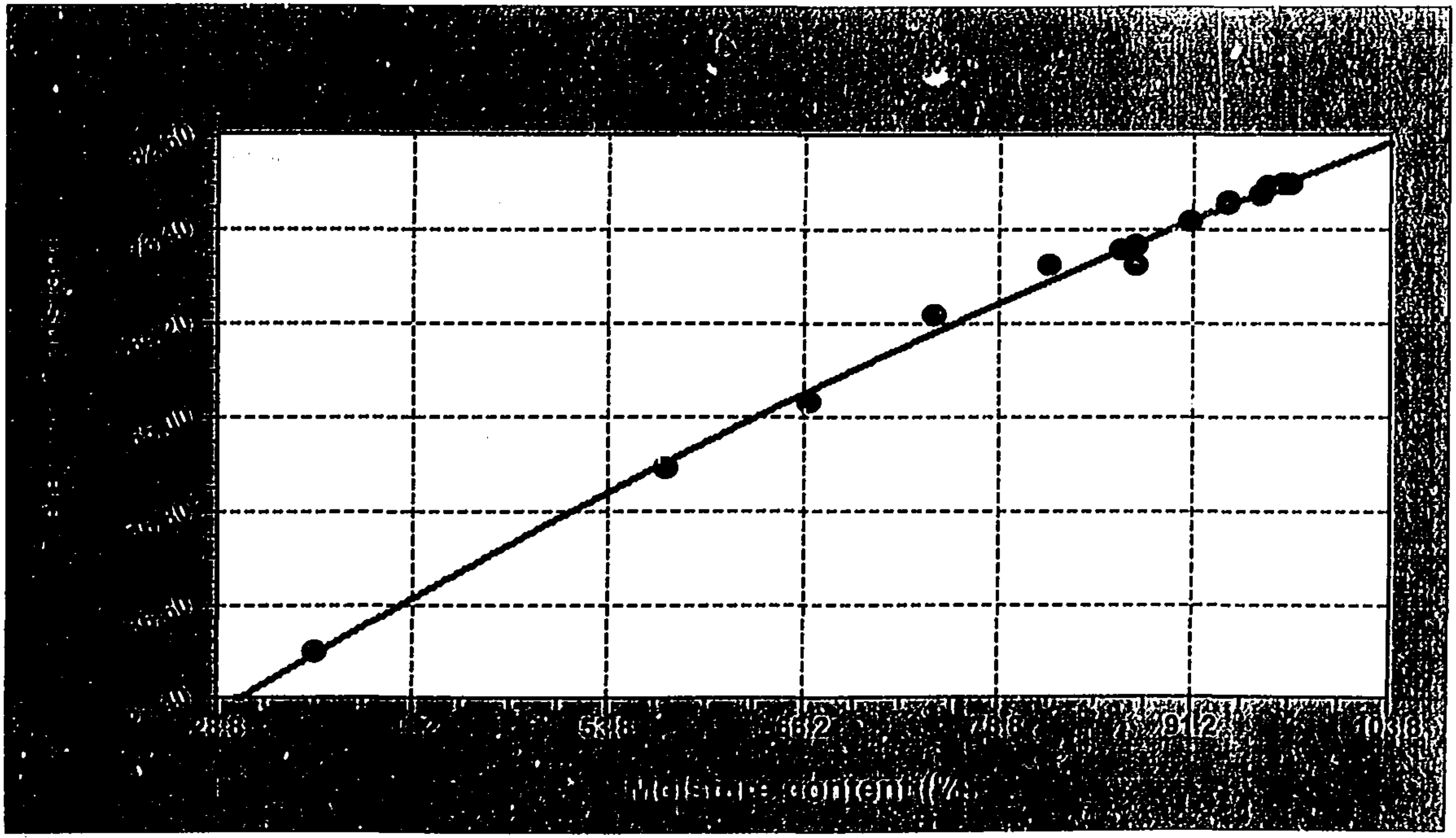


**Fig. 19** Dielectric constant of Maple syrup as a function of its moisture content at 25° C

Tulasidas et al. (1995) compared the dielectric properties of grapes with standard sugar solutions and have given the dielectric constants of sugar solutions with different concentrations of sugar. Since maple sap/syrup is more or less a sugar solution, these values are comparable.

It is observed that the dielectric constant exhibits a regular behavior with respect to moisture (Nelson, 1987) and many mathematical models have been developed, relating this property to moisture, frequency and density. In their study of the dielectric properties of grapes, Tulasidas et al. (1995) developed the following response surface model for dielectric properties of grapes.

$$\varepsilon' = -31.35 + 172.17M + 0.62T - 57.63M^2 - 0.74MT - 0.003T^2 \qquad (5)$$

$$\varepsilon'' = -8.70 + 78.95M + 0.11T - 50.34M^2 - 0.35MT - 0.00002T^2 \qquad (6)$$

where, T = temperature in °C, $25 < T < 80$ and

M = Moisture fraction on wet basis, $15 < M < 80$

This model (equation 5) was examined using the values for dielectric constant obtained for maple sap at a constant temperature of 25° C and the results are shown in Fig.19. The data fits the model fairly well ($R^2 = 0.9938$) and the slight deviation can be attributed to the possible errors in experiment.

### 4.3.2 Dielectric Loss

The dielectric loss observed at different stages of the processing as a function of moisture is shown in Fig 20. At higher moisture levels, the behavior of $\varepsilon''$ seems to be fairly linear and is seen to be lower at higher moisture content. Thus the behavior of the dielectric loss property of the maple sap indicates greater dielectric heating of the product at lower moisture levels.

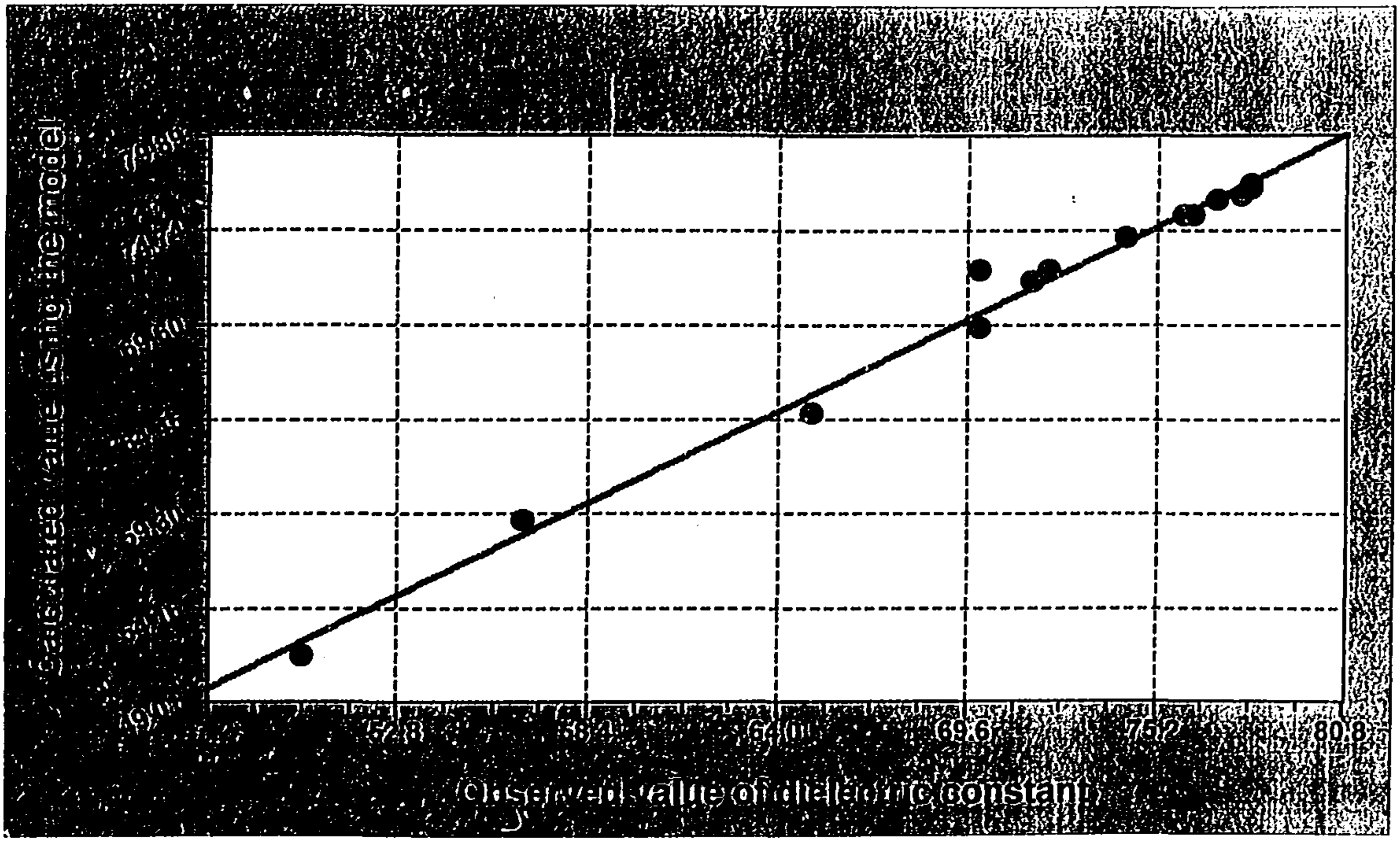


Fig. 20 Comparison of the observed values of dielectric constant with those calculated from the model of Tulasidas et al. (1995)

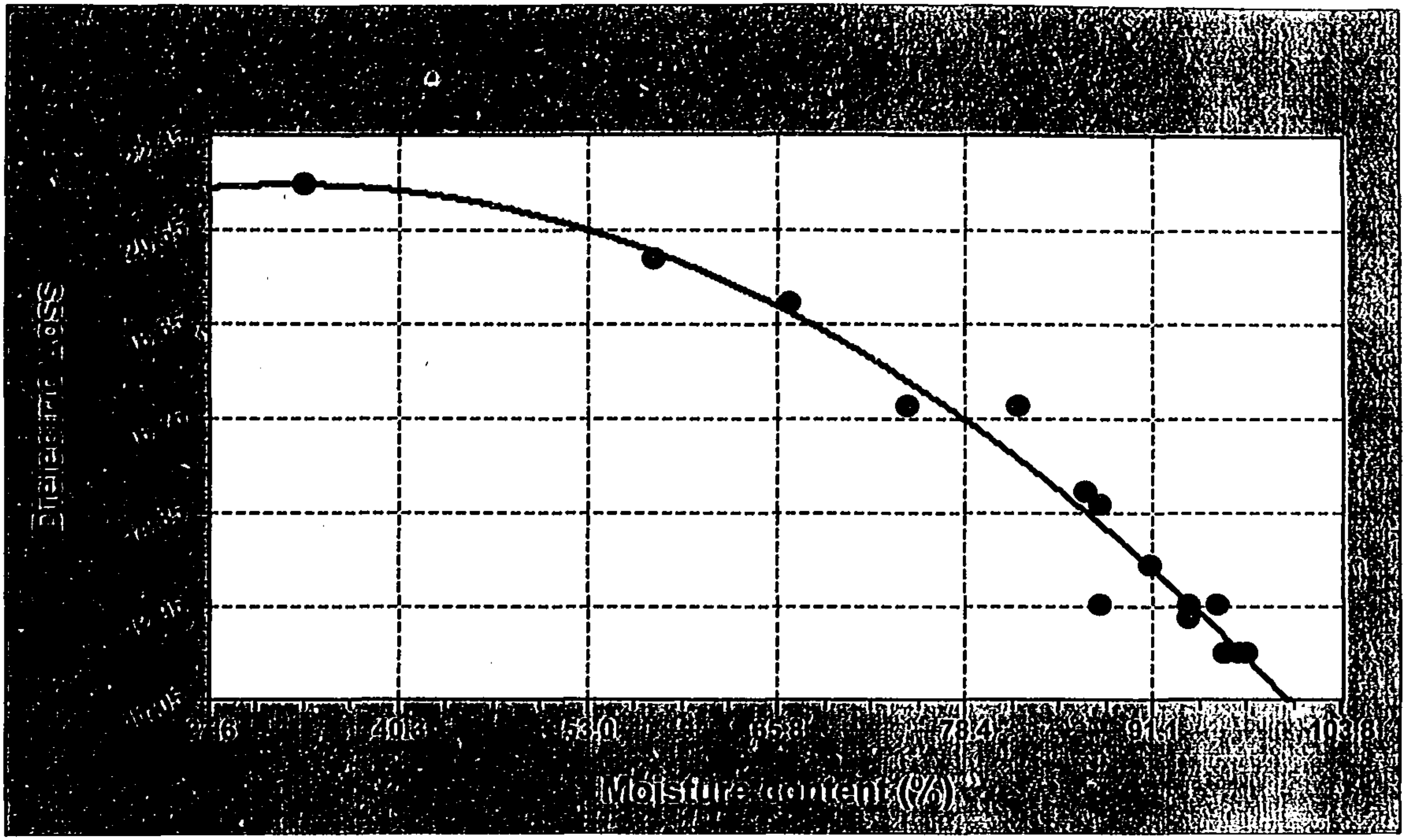


**Fig. 21** Behaviour of the dielectric loss factor of maple syrup at different moisture levels

This is an important factor which has a strong influence on the choice of microwave heating as a means of maple sap processing. The design of equipment for handling of large quantities of maple sap is a challenge in microwave heating. However, a closer look at the nature of the drawbacks in the conventional maple sap processing promises a beneficial role for dielectric heating. Due to the conductive and convective nature of heat transfer in the conventional methods, there is a large risk of local heating and burning of the product at the later stages of evaporation near the heating surface, causing discoloration or development of dark color along with strong undesirable flavors. The high viscosity and the slower heating rates are the chief reasons for this undesirable heat damage to the product and the prevention of this damage requires a careful design of the evaporator pan for good heat transfer rates and an efficient control over the processing by ensuring the appropriate flow rate of the syrup in the pan.

However, the dielectric behavior of maple sap might offer an effective remedy to this problem, which can ensure production of high grade maple syrup. Microwaves can be utilized for heating of the maple sap during the ending stages of evaporation i.e. for finish drying as a part of the processing setup. This can also handle the problem of bulk much better as the volume can be reduced initially by conventional means. But the dielectric loss is found to vary with the temperature. Tulsidas et al. (1995) who examined the variation of the dielectric loss factor of sugar syrups with temperature, indicate that the relation is inverse ie. the loss factor reduces with increase in temperature. Hence to achieve any meaningful application of this property, the behavior of the dielectric loss with variation in temperature needs to be examined for higher temperatures which are required for concentration of the maple sap.

But the review of literature has conflicting reports about the relationship between the moisture level of the food and its dielectric loss. At high moisture levels, some researchers have reported trends for dielectric loss increasing with moisture content (Bengtsson and Risman, 1971), decreasing with moisture content (Roebuck and Goldblith, 1972; Mudgett et al., 1980) and independent of moisture content (van Dyke et al., 1969; Ohlsson et al., 1974). It is fair to conclude that the dielectric loss shows little dependence on moisture content alone in the high moisture content range when the majority of water present in the food is in a free form.

The observed values for the dielectric loss obtained at a constant temperature of 25° C were compared with the empirical model given by Tulsidas et al. (1995) (equation 6) and the results are presented in Fig. 21. Clearly, the fit is generally very good ($R^2$=0.8914); however, the observed data also show significant scatter at points where repeated measurements were made, corresponding to higher moisture contents (lower Brix). This could be due to a combination of errors in the Brix and dielectric loss measurements.

Although this fit is generally very pleasing, it would have been preferable to have a model including higher temperatures as would be expected in a real syrup operation. The Tulasidas et al. (1995) model cannot be extrapolated to such temperatures because the predictive value decreases with distance from the center of the design used to develop it. New experiments should be performed to get accurate values of the dielectric properties at temperatures over 80° C.

### 4.3.3 Loss tangent

The values for loss tangent obtained at different moisture levels of the maple syrup at 25° C are shown in Fig. 22. It can be seen clearly that the loss tangent increases with the progress of the evaporation process. The loss tangent of the maple sap represented by a moisture content of 98% is 0.154 and that of the maple syrup, at which stage the moisture reduces to 35%, is found to be 0.6. The behavior fits to a quadratic equation with $R^2$ = 0.9978.

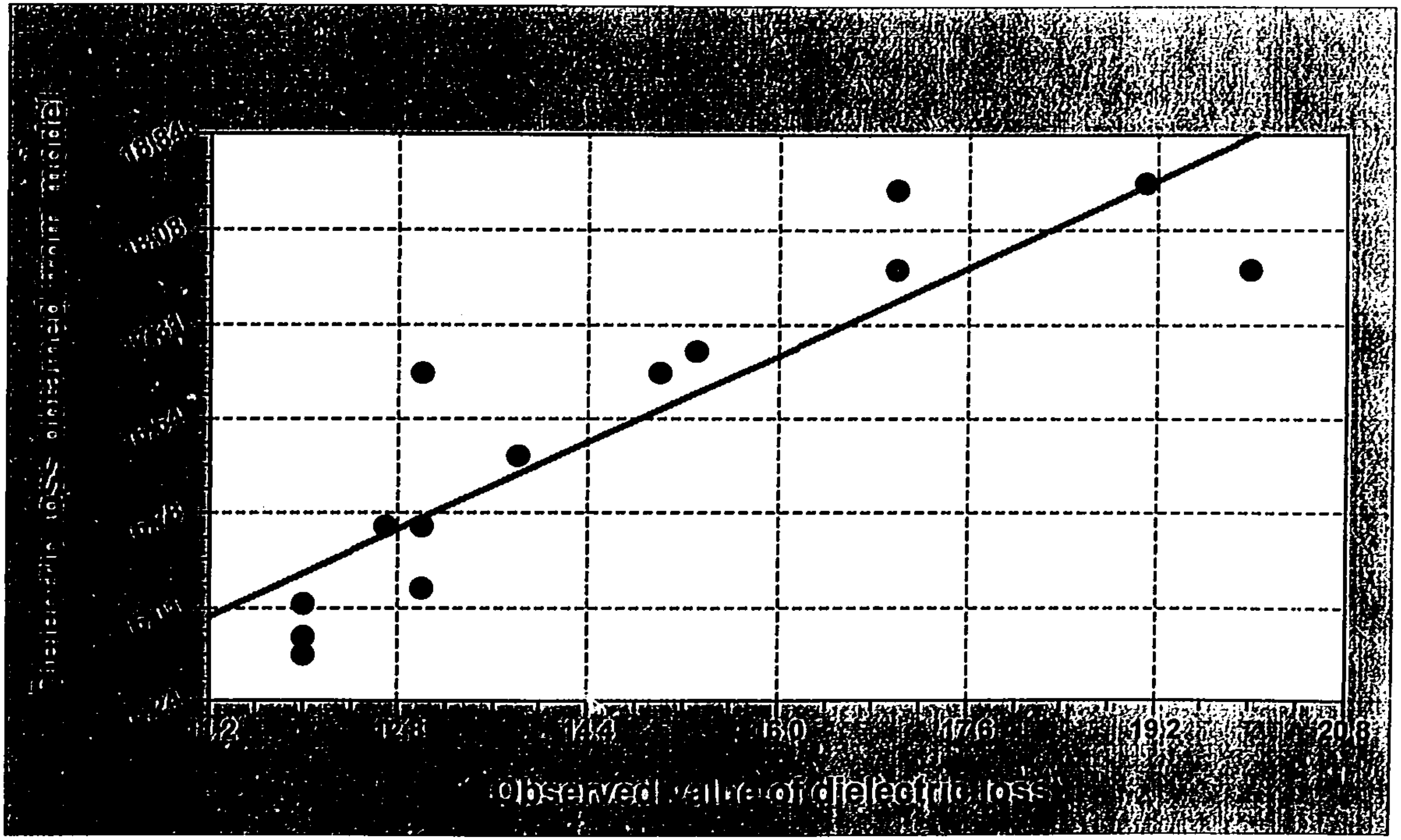


Fig. 22 Comparison of the observed values of dielectric loss with those calculated from the model of Tulasidas et al. (1995)

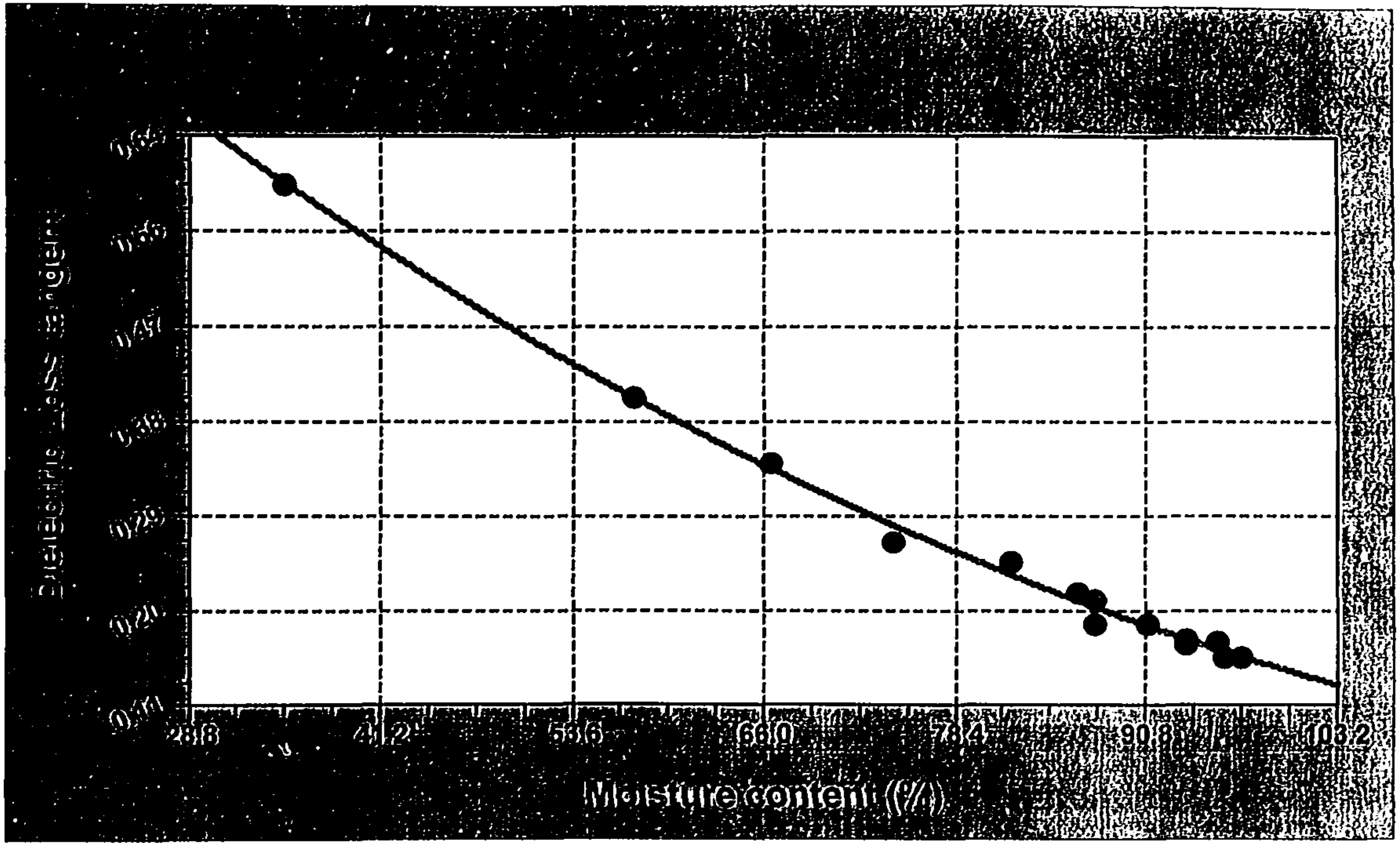


**Fig. 23** Behaviour of the loss tangent of maple syrup at different moisture contents

### 4.3.4 Electric Field Penetration Depth

The microwave penetration depth which is a function of wavelength and the dielectric properties of the material is an inherent limitation when the scaling-up strategies are considered. The penetration depth and in turn the power absorbed, have an inverse dependence on the dielectric loss factor. The study of this property is important in concentration and drying where for a fixed field intensity, the power-use efficiency and the depth uniformity of heating change with time.

The changes in the penetration depth occurring with the progress of the evaporation process is given in Fig. 23. The penetration depth was calculated by using the equation below, where ε' = penetration depth, tanδ = loss tangent and λ = wave length.

$$Z = \frac{\lambda}{2\Pi} \left| \frac{2}{\varepsilon' \sqrt{(1 + \tan^2\delta)} - 1} \right|^{1/2} \qquad (7)$$

The fit is quadratic ($R^2 = 0.9820$) and seems to behave quite regularly with a slight scatter. The penetration depth is as high as 9 cm at the sap condition and decreases with concentration. These values are important in designing the processing equipment for optimum utilization of the microwave power for heating and evaporation.

## 4.4 Summary

The different aspects of the dielectric behavior of maple sap at different moisture are necessary for considering the application of microwave heating for preparation of maple syrup. However, a detailed study regarding the variation of these properties with temperature, especially the higher temperatures which are necessary for removal of water from the sap, is called for. Such a study would go a long way in assessing the potential of microwave heating for maple syrup production. This is absolutely necessary for design of equipment and scaling up of the process.

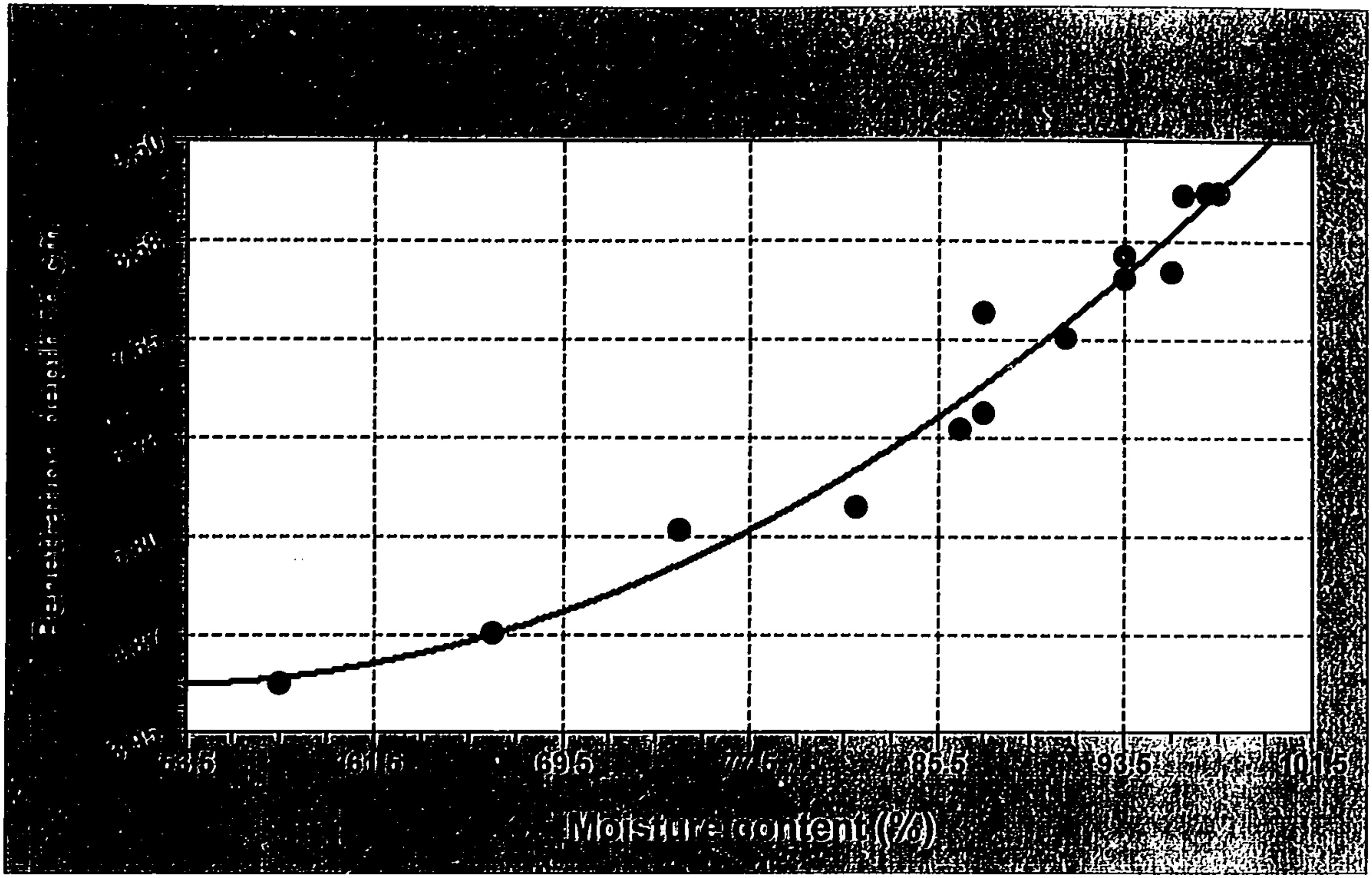


Fig. 24 Behaviour of the electric field penetration depth with varying moisture content

# CHAPTER FIVE

## 5. SUMMARY AND CONCLUSIONS

The study took a close look at the physical process of removal of water from maple sap to obtain maple syrup by microwave heating. During the process, some of the drying kinetics like the reduction of moisture content with time, the progress of the process in terms of increase in brix value and the power absorbed were studied and discussed. Maple syrup products were prepared starting from maple syrup by application of microwaves for heating. The products obtained were compared with commercial graded products for the quality and were found to be matching the highest standards prescribed by the industry. The dielectric properties of the maple syrup at different stages of concentration were studied and an attempt was made to verify the results using an empirical model that was proposed in an earlier study of the dielectric properties of sugar solutions.

This study can be regarded as only a beginning in what could be an exciting investigation into the potential of microwave applications in maple syrup industry. It is evident from the results obtained that microwaves can be successfully used for heating to obtain a high quality product. It could be a satisfying solution to the problems encountered during conventional heating process, where the nature of heat transfer poses a tough hurdle in achieving high quality.

However, there were some drawbacks, most of them inevitable due to the lab-scale approach, which need to be overcome for generating meaningful and practical results in any future study of this kind. The experiment needs to be structured in a manner that would lead to results which have practical value in terms of evaluating the power consumption, the time required for the process and engineering aspects like the scaling-up strategies and design of microwave processing equipment that suit the needs of the farm conditions. But these drawbacks were helpful in recognizing some of the factors that need to be concentrated upon for realizing the potential of this technology.

In a broader perspective, microwaves occupy an important position in the agricultural and food sector in the years to come. One of the recommendations that could be made on the basis of this study is the incorporation of microwave heating into a streamlined continuous process of maple syrup production, consisting of both the existing and the modern technologies available today. With the increasing interest of the farmers in the Reverse Osmosis process, a multistage process of concentration consisting of the membrane process at the initial stages, the conventional heating and the microwave heating at the final stages, which is crucial for control over the quality, can be envisioned. Thus, microwave heating technology can find its place among the candidates for the energy efficient processes.

While this study has proved that the potential exists and is quite exciting, any future study in application of microwave heating for maple syrup production should concentrate upon the power utilization and the energy efficiency aspects. A hard-core economic investigation to evaluate the extent to which the improvement in quality translates into increased revenue with a marginal cost/benefit analysis is a prerequisite for any practical approach. Besides, the dielectric properties of maple syrup at different stages of the concentration and at different temperatures should be studied for the purposes of design of the suitable equipment and process control.

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**Internet sites**

(A) http://www.pbpub.com/vermont (Vermont State)

(B) http://www.eb.com:195/cgi-bin (Encyclopeadia Britannica inc.)

(C) http://newcrop.hort.purdue.edu/hort/newcrops/crops (Perdue University)

(D) http://www.vir.com/~maplesyrup (Union des Producteurs Agricoles - Fédération des producteurs acéricoles du Québec)

# APPENDICES

## Appendix 1

### The electromagnetic spectrum

| Frequency (MHz) | Frequency tolerance (±) | Area permitted |
|---|---|---|
| 0.07 | 10 kHz | USSR |
| 13.56 | 0.05% | Worldwide |
| 27.12 | 0.6% | Worldwide |
| 40.68 | 0.05% | Worldwide |
| 42, 49, 56, 61, 66 | 0.2% | Great Britain |
| 84, 168 | 0.005% | Great Britain |
| 433.92 | 0.2% | Austria, Netherlands, Portugal, West Germany, Yugoslavia, Switzerland |
| 896 | 10 MHz | Great Britain |
| 915 | 13 MHz | North and South America |
| 2 375 | 50 MHz | Albania, Bulgaria, Hungary, Rumania, Czechoslovakia, USSR |
| 2 450 | 50 MHz | Worldwide except where 2,375 MHz is used |
| 3 390 | 0.6% | Netherlands |
| 5 800 | 75 MHz | Worldwide |
| 6 780 | 0.6% | Netherlands |
| 24 150 | 125 MHz | Worldwide |
| 40 680 | | Great Britain |

Appendix 2

## The ISM frequencies of microwaves