Performance Optimization of a Multi-slotted Waveguide for Microwave Processing Applications

by

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ABSTRACT

Microwave power is seen as a promising alternative to conventional methods for drying freshly harvested grains to safe storage moisture levels. In an attempt to elaborate a continuous flow microwave dryer, the optimum operating characteristics of a prototype microwave antenna were investigated during a low power microwave drying simulation with corn at three different moisture content levels (15%, 23% and 30% w.b.). The antenna consisted of a slotted waveguide with the orientation and width of the slots being the main points of investigation.

The optimum angle of the slots with respect to the direction of propagation of the travelling wave was found to be in the neighbourhood of 55° at all moisture contents. Slots 13 mm wide gave better results than the 6 mm ones which are often suggested in literature.

RÉSUMÉ

L'usage de microondes est envisagé comme une alternative prometteuse pour le séchage du grain jusqu'à des taux d'humidité assez bas pour fins d'entreposage. La présente recherche a été effectuée dans le but de jeter les bases pour l'élaboration future d'un séchoir à grain microonde fonctionnant en mode continu. Elle vise l'approfondissement de la connaissance des caractéristiques optimales d'opération d'une antenne microonde lors d'une simulation de séchage microonde de maïs à différents taux d'humidité (15 %, 23% et 30%). L'antenne utilisé est du type guide d'onde à fentes rayonnantes et les principaux paramètres étudiés furent l'orientation et la largeur des fentes.

L'angle d'inclinaison optimal des fentes par rapport à la direction de propagation de l'onde progressive a été évalué autour de 55° indépendamment du taux d'humidité. Les fentes les plus larges, ayant une largeur de 13 mm, ont donné de meilleurs résultats que les fentes de 6 mm de large qui sont souvent suggérées dans la littérature.

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LIST OF SYMBOLS

$\varnothing$	=	slot inclination angle (°)
λ_o	=	free space wavelength (m)
c	=	speed of light travelling into free space, 3.0×10^8 (m/s)
f	=	frequency (Hz)
ε^*	=	complex permittivity
ε'	=	dielectric constant
ε''	=	dielectric loss factor
ε_o	=	permittivity of free space ($8.854*10^{-12}$ F/m)
j	=	complex operator
δ	=	loss tangent or dissipation factor
GHz	=	giga hertz (10^9 Hz or s^{-1})
MHz	=	mega hertz (10^6 Hz or s^{-1})
d.b.	=	dry basis
w.b.	=	wet basis
pd	=	penetration depth (m)
P	=	power dissipation (W)
E	=	electric field strength (V/cm)
f	=	frequency (Hz)
v	=	volume of material (cm^3)
ρ	=	density of the material (g/cm^3)
T	=	material temperature (°C)
C_p	=	specific heat (J/g°C)
t	=	time (s)
TM_{mnk}	=	transverse magnetic; directions x,y,z
TE_{mnk}	=	transverse electric; directions x,y,z
Q	=	quality factor of a cavity
λ_g	=	guided wavelength (m)

Pi	=	Incident power (W)
Pr	=	Reflected power (W)
Pt	=	Transmitted power (W)
Pa	=	Absorbed power (W)
dB	=	decibels
dBm	=	decibels
S_{11}	=	reflection as measured by network analyzer (dB)
S_{21}	=	transmission as measured by network analyzer (dB)

I INTRODUCTION

1.1 Background

Drying of freshly harvested grains to safe storage moisture content level is commonly accomplished by convection drying using fossil fuel combustion. The drying process is characterized by a simultaneous heat and mass transfer. When hot air is used to dry grains, a slow conduction heat transfer takes place from the grain surface towards the inside. A temperature gradient is developed across the particle with lower temperatures in layers of higher moisture. The outer layers of the kernel are dried first and become less permeable, creating case hardening (Fanslow et Saul., 1971) and inhibiting moisture transfer from within the particle to the surface.

Microwave energy can be used to overcome this problem and speed up drying because heating occurs within the particle due to radiative transfer. When microwaves are used to dry grains, the heat generation inside the kernel is instantaneous and causes a relatively rapid mass transfer of moisture emerging out. Researchers have studied the drying behavior of particulate food materials in a microwave field (Hall, 1963; Fanslow and Saul, 1971; Bhartia et al., 1973; Shivhare et al., 1991).

Shivhare (1991) thoroughly studied the drying behavior of corn in a microwave field. He established a diffusion model based on varying surface conditions. The model well described the microwave drying behavior of corn over a wide range of initial moisture contents, inlet air conditions and absorbed powers. Seed quality grains could be dried with power levels of 0.25 W/g and feed quality grains obtained with power levels below 0.75 W/g. However, the experimental work was performed in batches.

Operational microwave-vacuum dryers were built and tested for drying grains in the 1970's and 80's (McDonnell Aircraft Co., 1977, Ken Bratney Co., 1982). These continuous flow or semi-batch dryers consisted of large stationary units which could accomplish drying of the product from harvest moisture content (25-30 % w.b.) to safe storage levels (14-18 % w.b.). The amounts of microwave power required to obtain capacities in the order of tons per hour necessitated either the presence of a huge magnetron or a large quantity of smaller ones, resulting in a very high initial cost of the equipment. The lower energy consumption is often insufficient to justify these costs compared to the cheaper convection drying equipment.

Enlightened by these facts, a different approach is considered in the present research. The focus is kept on developing equipment which would be more compatible with the existing grain conveying and drying facilities. Reducing the size of the dryer or the amount of moisture to be removed are expected to be solutions to the equipment cost problems. Microwave power could be used as a pre-processing tool to raise the temperature of the grain more efficiently than the conventional method. It could also be used in a dryeration system that helps remove moisture in final phase of drying for safe storage. A combination of microwave with conventional drying methods accomplishing the bulk of the drying task might be desirable (Tulasidas, 1994). In recent years, the mass production of magnetrons to serve as microwave energy sources for domestic and industrial microwave ovens has lowered the costs of energy sources so that other new applications might be considered (Nelson, 1987).

The present work suggests the use of the slotted waveguide antenna technique to couple microwave power to the material. It is compatible with the idea of developing a continuous process dryer. Slotted waveguides have been successfully used to couple electromagnetic energy to materials for heating and drying purposes (Rueggeberg, 1980; Metaxas and Meredith, 1983) and for plasma applications (Ji and Gerling, 1988; Sauvé et al., 1993). Actual grain drying and storage facilities often use grain moving equipment in which the material travels in a closed tubular channel. This is well demonstrated in the equipment such as screw and pneumatic conveyors. One could imagine that the microwave applicator could be implemented on the walls of the conveying tube to obtain a continuous flow drying while transporting the grain between two points of the processing plant. Of course, adequate means of preventing wave leakage must be utilized.

Before the completion of a dryer of this type, certain basic radiation characteristics of the slotted waveguide applicator have to be investigated.

1.2 Objective

The objective of the present work was to study the radiating characteristics of a slotted waveguide antenna mounted in a setup that simulates the coupling to a grain conveying tube. The effect of the slot inclination angle Ø and the shape of the slots as well as monitoring of the grain moisture contents of corn were the main points of investigation.

1.3 Scope

Only low power measurements were possible with the setup used. The main focus is to set the bases for further work in which the actual dryer could be built. Limiting factors did not allow for the testing of the equipment under high power levels. Further research would be required to match the impedance of the antenna to the load in order to obtain maximum radiation. Other grains could be the scope of further studies. The completion of the actual dryer, which could recirculate the microwaves through several waveguide antennae is beyond the scope of this study.

II REVIEW OF LITERATURE

2.1 Grain drying technology

Drying of an agricultural crop is a process involving simultaneous heat and mass transfer in which the moisture content of the wet material is reduced to safe storage level. In hot, dry countries, solar energy and natural air drying can be used to dry the crop. In countries where the climate is more humid, artificial drying must be used. Early harvest of rice is made possible by artificial drying, bringing about a reduction in field losses due to weather, birds, pests, or shattering. It also allows for a longer harvest time, reducing the high seasonal labour needs, and also makes the harvested land available for other purposes such as grazing and double cropping (Richard and Raghavan, 1984). However, in eastern Canada, where temperatures are cool and humidity is high, artificial drying is necessary due to the shorter growing season which doesn't allow for natural drying in the field. Corn, for example, can be harvested at 35% moisture content with an average around 30%. Considering a safe moisture level for year long storage of corn to be in the neighbourhood of 13% (Hall, 1980) suggests the need for efficient methods of crop drying. Corn and beans are the crops most often dried artificially in Canada and the United States.

In an artificial grain drying process, the transfer of heat to the kernels may be accomplished by convection, conduction, or radiation.

2.1.1 Convection drying

The most common method of artificially drying grain is by using air as the heating medium. A fan is usually used to force heated air through a fixed bed of grain, producing a moisture diffusion process which results in drying. Convection drying is a relatively inefficient process since the air will reach saturation before using all its sensible heat for moisture removal (Foster, 1973). Using higher air temperatures may increase the drying rate, but also results in kernel damages and moisture gradient through the grain bed (Brooker et al., 1992).

2.1.2 Conduction drying

Early research on a grain dryer using conduction heating was reported by Chancellor (1968), in which the grain was placed on top of a steel plate heated to 93.3°C. He suggested the use of a granular medium, such as sand, to reduce localized heating. Khan (1973) reports the use of heated sand as a conductive heat transfer medium for a low cost rapid method of drying rice. Moisture content of the rice was brought from 32 to 18% (d.b.) during a 15 to 20 sec. exposure to sand heated to about 200°C. Conduction drying takes place when heat is supplied to a solid medium which comes in contact with the grain. The drying method, called "Particulate Medium Conduction Grain Drying", consists of immersing the grain in a hot bed of granular material, such as sand or salt, for a very short "contact time" during which most of the drying takes place (Sibley and Raghavan, 1985). The grain is then separated from the drying medium which is recircultated in the dryer. The potential use of drying media such as sand, salt, steel balls, aluminum and glass beads as well as zeolites has been examined (Lapp and Manchur, 1974; Lapp et al., 1976; Raghavan et al., 1988; Tessier and Raghavan, 1984; Sotocinal, 1997).

2.1.3 Radiation drying

Radiation heating exists in different forms among which induction and dielectric heating have been gaining in popularity in recent decades. Induction heating is the result of the interaction of an electromagnetic field with a conducting material at frequencies below high frequencies. It is governed by principles which rely on current theories and is of lesser interest here due to the insulating properties of grain materials. However, when energy in the form of high frequency electromagnetic waves is applied to an insulating material, radiation heating also occurs. This is caused by the ability of the electric field to polarize the charges in the material and the inability of this polarization to follow extremely rapid reversals of the electric field, resulting in the dissipation of power within the insulating material (Metaxas and Meredith, 1983). "Lossy" materials are those which easily absorb microwaves (Shivhare, 1991). At microwave frequencies, the free and bound polar water molecules present in grain kernels are heated when subjected to electromagnetic energy. For example, a corn kernel at harvest might contain 48.2% water (w.b.) in the germ, which is much more than in the surrounding endosperm with 30.7% water (Brooker et al., 1992). Knowing that the germ constitutes the central part of the kernel leads to the conclusion that the temperature gradient developed inside the kernel is opposite to that developed by convection and conduction heating. During dielectric drying of grains, the maximum temperatures are found at the center of the kernel, resulting in an increased rate of moisture removal. Most of the experiments found in literature using microwave to dry grains mention the use of an air flowing stream to carry the moisture removed out of the kernels. This forced air flow can also be replaced by vacuum which will also help reduce the boiling point of water and thus lower the drying temperature. Variables affecting the absorption of the energy are the frequency and the dielectric properties of the material, which are themselves frequency dependent (Nelson, 1987).

2.2 Microwaves

Electromagnetic waves are emitted from all bodies above absolute zero temperature. Microwaves are high frequency electromagnetic waves composed of an electric and a magnetic field. Figure 2.1 shows a schematic of an electromagnetic wave travelling into free space. Note that the electric field (E) and magnetic field (H) components are perpendicular to each other. The frequency range of microwaves is from 300 MHz to 300 GHz, equivalent to wavelengths of 1 mm to 1m. The relation between wavelength and frequency is defined by:

$$\lambda_o = \frac{c}{f} \tag{2.1}$$

where:

λ_0 = free space wavelength (m)

c = speed of light travelling into free space, 3.0 x 10^8 (m/s)

f = frequency (Hz)

The most widely used frequencies in the ISM (Industrial, Scientific and Medical) band in North America are 915 MHz and 2.45 GHz. Figure 2.2 shows the electromagnetic (EM) spectrum, where the microwave frequency range lies between radio frequency (RF) and infrared (IR). The advent of radar technology together with the development of the magnetron during the second World War established a unique challenge to put such devices for generating microwaves into peaceful and profitable use. Globally, the most frequent uses of microwaves occur in communication, radar and navigation, heating and physical diathermy. In the food industry, microwaves are used for drying, blanching, thawing, pasteurization and sterilization (Shivhare, 1991).

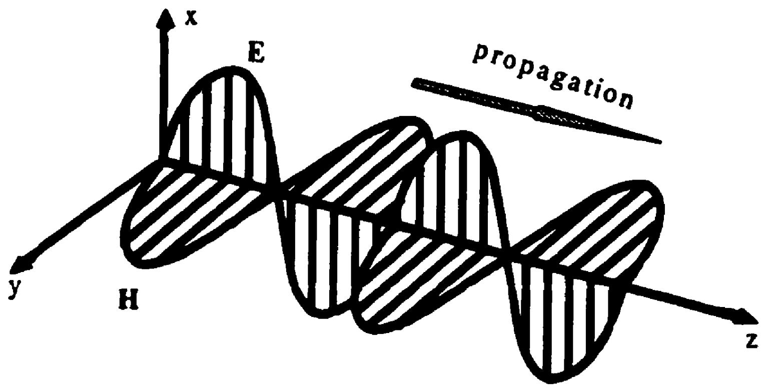

Figure 2.1 Electromagnetic wave travelling in free space

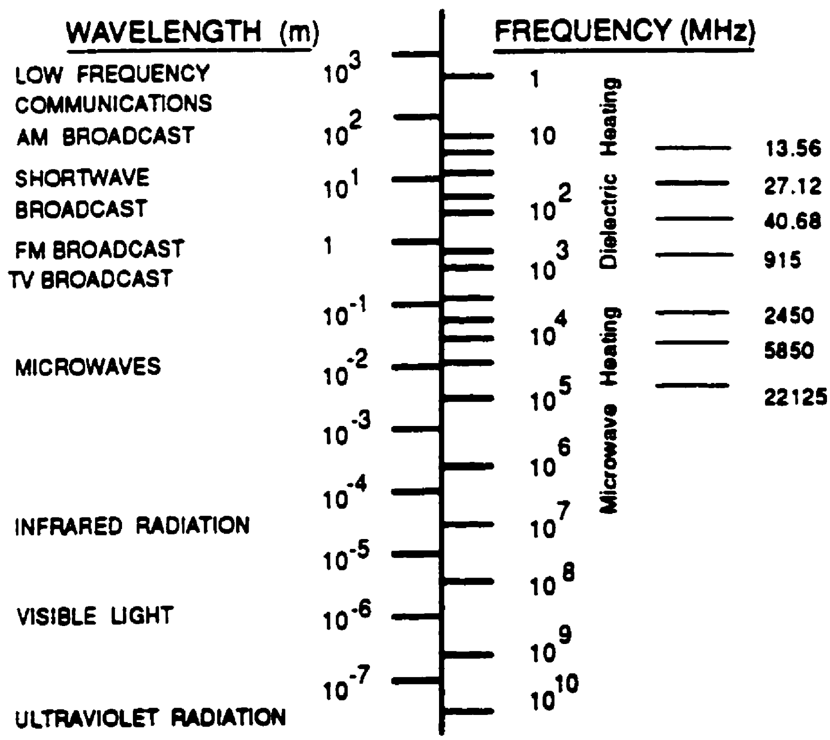

Figure 2.2 The Electromagnetic spectrum

2.2.1 Polarization

The interaction of an electric field with a dielectric material has its origins in the response of charge particles to the applied field (Metaxas and Meredith, 1983). The displacement of these charge particles from their equilibrium positions gives rise to induced dipoles which respond to the applied field. This induced polarization can be caused by the displacement of electrons around the nuclei (electronic polarization) or by the relative displacement of atomic nuclei due to unequal distribution of charge in the molecule (atomic polarization). Some dielectric material, classified as polar dielectrics, contain permanent dipoles due to the asymmetric charge distribution of unlike charge partners in a molecule.

The polar molecule of water is one good example of a molecule arranged in a permanent dipole with asymmetric charge distribution that tends to realign under the influence of an alternating electric field. This phenomenon is called dipolar or reorientation polarization and is probably the most significant in generating heat during microwave processing of materials (Hasted, 1973). Figure 2.3 depicts the action of the alternating electric field on the polar molecules. The movement of the molecules produces a rise in temperature and thus results in heating, and eventually drying, if the action is maintained over sufficient time. There is another source of polarization arising from charge build-up in interfaces between components in heterogeneous systems. It is referred to as interfacial, space charge or Maxwell-Wagner polarization.

2.2.2 Dielectric properties

Dielectric properties of a material are of primary importance to the design of microwave heating and processing applications due to their effect on the absorption of electromagnetic energy by the material. The most

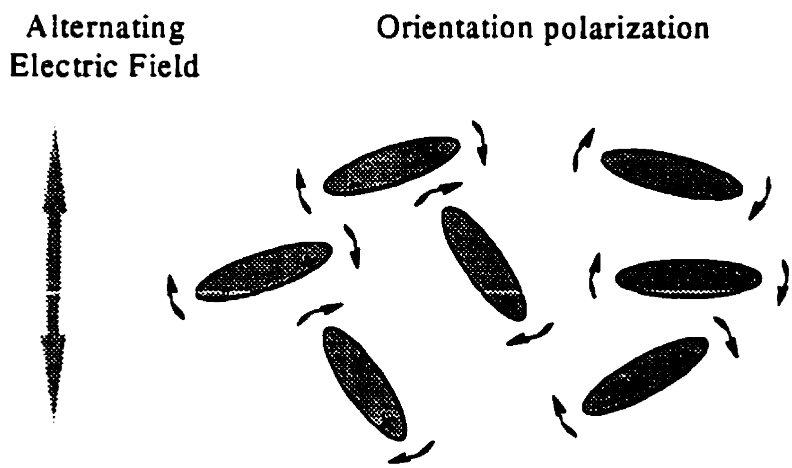

Figure 2.3 Effect of the alternating electric field on the polar molecules

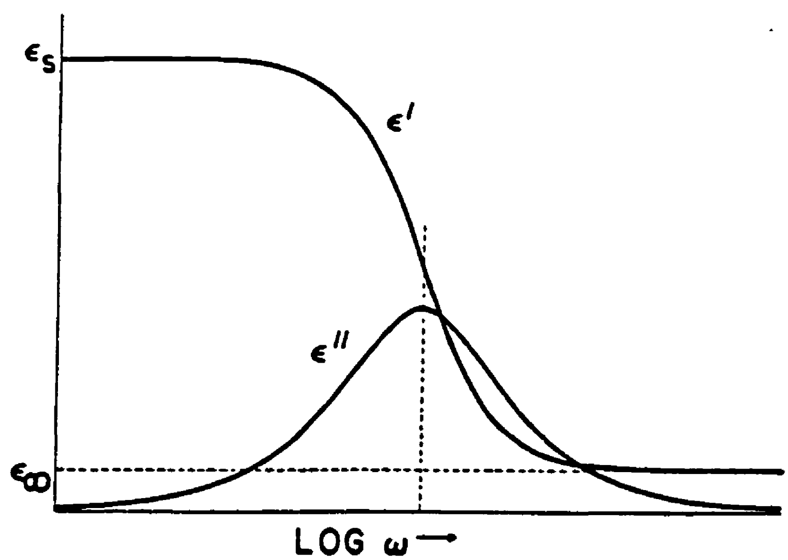

Figure 2.4 Dispersion and absorption curves representing the Debye model for a polar substance with a single relaxation time. (Nelson, 1991)

important factors affecting dielectric properties of particulate materials are moisture content, bulk density and temperature as well as the frequency of the alternating field. Dielectric properties are often expressed in the form of complex permittivity:

$$\varepsilon^* = (\varepsilon' - j\varepsilon'')\varepsilon_o \tag{2.2}$$

where:

ε^* = complex permittivity

ε' = dielectric constant

ε'' = dielectric loss factor

ε_o = permittivity of free space ($8.854*10^{-12}$ Farad / meter)

j = complex operator

The dielectric constant and the dielectric loss factor are respectively the real and imaginary part of the complex permittivity. The dielectric constant is a measure of the ability of a material to couple electromagnetic energy whereas the loss factor is associated with the capacity of a material to heat by absorbing microwaves (Tulasidas, 1994). The ratio of the dielectric loss factor over dielectric constant is called loss tangent and represents the ability of the material to generate heat (Mudgett, 1990). It is expressed in the form:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2.3}$$

where:

δ = loss tangent or dissipation factor

The dielectric properties of food materials are strongly affected by their moisture content and the frequency of the electromagnetic field primarily due to the dipolar nature of the water molecule. The concept of a single relaxation time introduced by Debye (1929) is a simple way of describing the effect of frequency on the dielectric properties of dipolar materials. At low frequencies, near d.c., the dipoles have ample time to follow the variations of the applied field and the dielectric constant is at its maximum value; that is, the bound charge density attains its maximum value and all the energy of the external source is stored in the material. As the frequency increases the dipoles are unable to fully restore their original positions during field reversals and as a consequence the dipolar polarization lags behind the applied field. As the frequency increases further a point is reached where the reorientation polarization fails to follow the applied field and contributes less to the total polarization. The fall of the effective polarization manifests itself as a fall in the dielectric constant and a rise in the loss factor. Energy is now drawn from the system and is dissipated as heat into the material. Figure 2.4 illustrates the Debye model for polar materials with single relaxation time. Free water in its liquid state is a good example of a polar dielectric.

However, few materials of practical interest exhibit such properties. Most often, water is physically absorbed in material capillaries or cavities or chemically bound to other molecules of the material. Dielectric relaxations of absorbed water take place at lower frequencies than the relaxation of free water (Hasted, 1973).

As we noted earlier the most important factors affecting the dielectric properties of grains are the moisture content and temperature as well as the frequency of the alternating field (Nelson, 1982). At microwave frequencies of 300 MHz and 2.45 GHz and at a temperature of 24°C, the dielectric constant of corn was increasing with an increase in moisture whereas the dielectric loss factor was less regular in its dependence on moisture content (Nelson, 1979). For a given moisture content, the dielectric constant was found to decrease with increasing frequency where as the dielectric loss factor didn't show a regular pattern. The temperature dependence of the dielectric constant was found to be nearly proportional at temperatures below 60°C and moisture contents below 20% (d.b.) but non linear at higher moisture content. The loss factor is hard to relate to temperature due to its complicated dependence on the other factors such as frequency and moisture content.

Density has also been identified as a major source of variation for ε' and ε" (Kent, 1977; Nelson, 1983a,b; Nelson 1984a,b; Nelson and You,1989). The density dependence of the dielectric properties of particulate materials must be accounted for in elaborating functions determining grain moisture content (Powell et al. 1988; Meyer and Schilz, 1980). In the case of moisture determination by microwave methods, the frequency used should be above 5 GHz to avoid the influence of ionic conductivity and bound water relaxation (Kraszewski, 1988). For this reason, dielectric properties vs density relationship studies have been concentrated to high frequencies.

However, the size of microwave components is usually proportional to the wavelength and therefore, inversely proportional to frequency. If microwave power is to be applied to grain for drying purposes, the size of the dryer to accommodate reasonable processing rate will suggest the use of lower microwave frequencies. St-Denis et al. (1995) have validated established relationships between roots of the dielectric properties and density for pulverised grains tested with the cavity perturbation method. The frequency of 915 MHz used in that experiment is typical for industrial microwave application. Figure 2.5 and 2.6 show the results for corn.

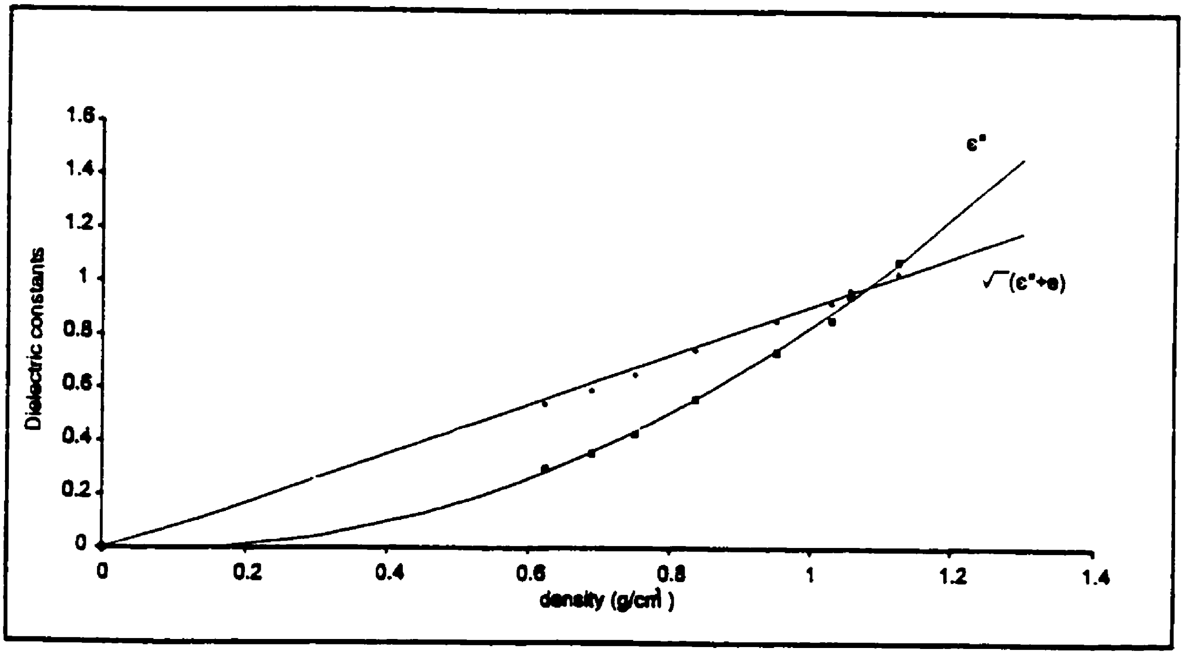

Figure 2.5 Functions of ε"vs bulk density for a sample of pulverized corn.

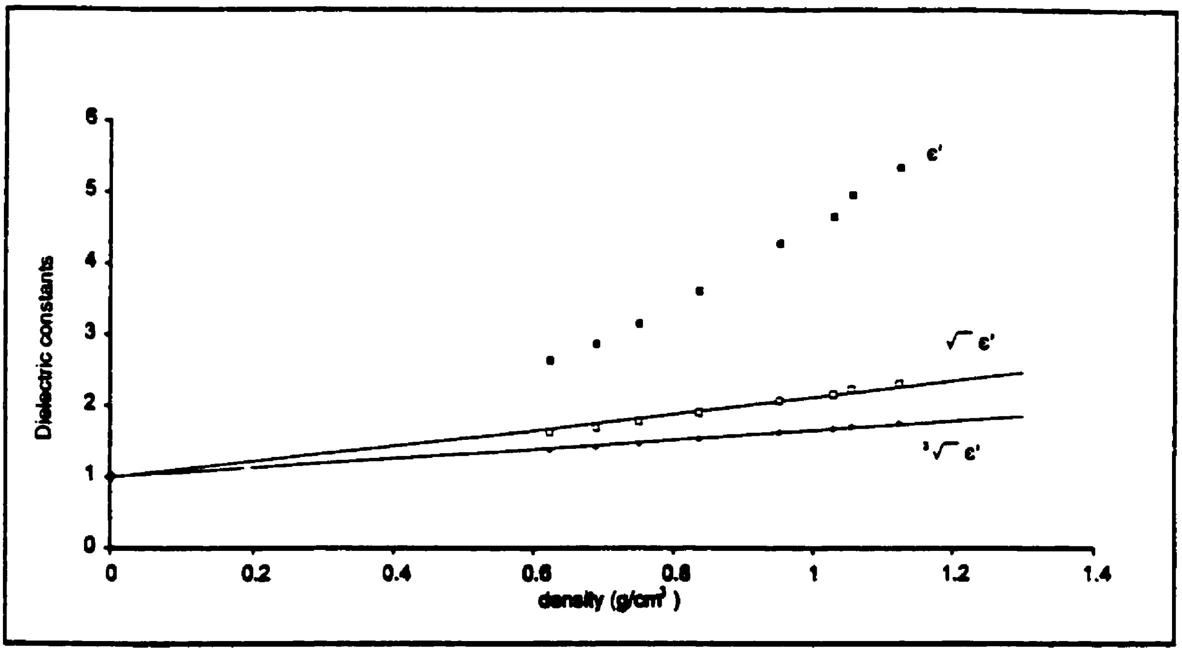

Figure 2.6 Functions of ε' vs bulk density for a sample of pulverized corn.

2.2.3 Penetration depth

The dielectric properties of a material also affect the power attenuation of the electromagnetic waves as they penetrate the lossy material. Penetration depth is defined as the distance from the surface of the material at which the power drops to 1/e (36.8%) from its value at the surface and is expressed by:

$$pd = \frac{\lambda_o \sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{2.5}$$

where:

pd = penetration depth (m)

λ_o = free space wavelength (m)

Penetration depth increases with longer wavelengths or in other words decreases with increasing frequency. For a given frequency, the penetration depth increases with the dielectric constant but decreases with the loss factor which has a more pronounced effect due to the form of the relationship in the above equation. In general, the penetration depths at frequencies below 100 MHz are in the orders of metres and present little problems as far as power penetration unless the loss factors are exceedingly high. At microwave frequencies however, the penetration depth are correspondingly smaller and often the size of the material to be treated is larger than pd and microwave heating could result in unacceptable non-uniformities in the temperature distribution (Metaxas and Meredith, 1983). The effect of temperature on the penetration depth of different foodstuffs has been studied by Ohlsson et al. (1974). They report higher penetration depths at lower temperatures and frequencies, but this effect was less important at temperatures above 0°C than for frozen conditions. For corn, the irregular changing of the dielectric loss factor with temperature and moisture content makes the prediction of the penetration depth during the drying process a tedious task. Systematic studies on the effect of these parameters should be encouraged.

2.3 Microwave heating and drying

Microwave heating and drying of grain is a volumetric process which is distinctive from other conventional drying mechanisms. The heat is generated inside the material by the selective absorption of electromagnetic energy by water molecules, creating an instantaneous moisture transfer out of the material where as most of the other drying techniques involve slower conduction heat transfer through and inside the kernel to generate the moisture transfer.

2.3.1 Volumetric heating

The volumetric dissipation of microwave power into heat in the material is dependent upon the intensity and frequency of the field as well as on properties of the material such as temperature, specific heat, dielectric loss factor, density and volume. The relationships are:

$$P = 55.63 * 10^{-12} \; f \varepsilon'' E^2 \; v \qquad (2.5)$$

$$\frac{dT}{dt} = \frac{P}{\rho \, v \, C_p} = \frac{55.63 * 10^{-12} \; f \varepsilon'' E^2}{\rho \, C_p} \qquad (2.6)$$

where:

P = power dissipation (W)

E = electric field strength (V/cm)

f = frequency (Hz)

v = volume of material (cm^3)

ρ = density of the material (g/cm^3)

T = material temperature (°C)

C_p = specific heat (J/g°C)

t = time (s)

2.3.2 Grain drying with microwaves

The use of microwaves at 2.45 GHz for heating and drying particulate food materials such as corn has been studied by several researchers (Hall, 1963; Fanslow and Saul, 1971; Bhartia et al., 1973; Hamid et al., 1975;McKinney et al., 1977; Ken Bratney Co., 1982 and Shivhare et al., 1991).

Hall (1963) used a microwave oven to dry samples of corn from 34 to 42% initial moisture content (d.b.) to 18%. Samples of 500 g were dried in about 6.5 minutes, resulting in damaged kernels due to high drying rates. He observed damages ranging from discoloration of a few kernels to severe cracking and burning of grains. A control experiment with a 500 g sample put in an air oven at 110 °C resulted in a drying time of 53 min.

Fanslow and Saul (1971) used a combination of microwave and unheated air to dry corn at 2.45 GHz. Preliminary drying tests without air flow resulted in severe damages to corn which was cracked or puffed. A 1.8 kW generator was used with samples of 0.625, 1.25 and 2.5 kg of corn combined with three levels of air flow rates ; 26, 39 and 52 cfm. The drying trials brought the corn from 22.2% moisture content to 11.8% and resulted in severe damages to kernels such as burning, cracking or puffing. However, the time spent before noticeable damages occurred was increasing with increasing air flow rates. There was no significant effect of the air flow rate on the drying rate of corn. The experiment showed no difference between the drying rates of freshly harvested and re-wetted corn.

Bhartia et al. (1973) used hot air in combination with microwaves to dry sand, potato starch and silica gel. The samples were spread in a thin layer on a Teflon tray and the moisture loss recorded continuously. The moisture content was reduced from 16.3% for sand, and from 29.9% for potato starch and silica gel to the bone-dried state. The temperature of the hot air used varied between 23.9 and 90.6°C and microwave power levels of application ranged from 3 to 37.5 W/g. The use of hot air achieved an important reduction in the drying time.

Hamid et al. (1975) developed a continuous flow microwave bean roaster which used hot air as a pre-heating and moisture carrier medium. Heat treatment of soybeans and other seeds and beans for the destruction of the anti-trypsin enzyme is conventionally carried out using hot air. The microwave applicator that they have developed is presented in Figure 2.7. It consists of a hopper, a perforated low loss dielectric tube for propagation of microwave energy, and a double walled cylindrical cavity (with hot air exhaust perforations in the inner wall). During drying trials, moisture and temperature were continuously monitored by sensors which feed information to a control system to adjust power level, flow rates, etc., necessary for a satisfactory quality and nutritious product. The authors have estimated the total energy requirements to be approximately 66% of those required by the conventional process.

McDonnell Aircraft Co. (1977) developed a microwave drying process for particulate food materials. The MIVAC™ is a microwave-vacuum system consisting of a stainless steel cylindrical column 9.1 m high by 0.9 m diameter (McKinney et al.,1977). The use of vacuum allows to reach the boiling point of water at lower temperatures, resulting in a better quality of the material. It was reported that an operating pressure of 8 kPa produced a drying temperature of 41.7°C for corn. The authors claimed an energy requirement of 38% to 61% that of conventional drying systems for corn with germination values ranging between 75 and 81%. The MIVAC system (see Figure 2.8) is available in horizontal and vertical configuration and is expected to perform drying on corn, peanuts, wheat, rice, numerous fruits, peppers, tomatoes, soy protein, milk powder, coal fines, books, documents, papers and fabrics. A continuous process system, the GIGAVAC™ is also available for industrial drying purposes.

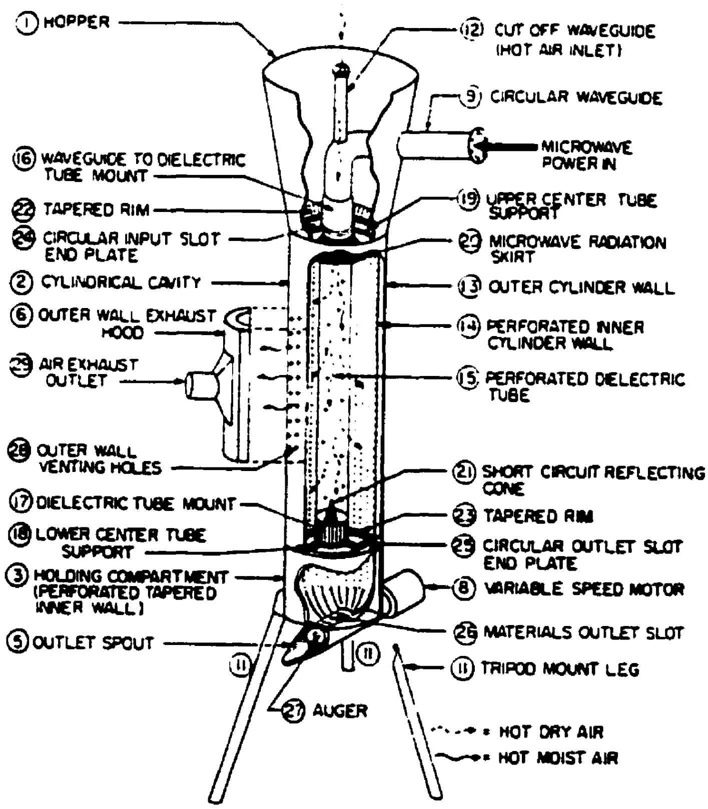

Figure 2.7 Microwave bean roaster (Hamid et al. 1975)

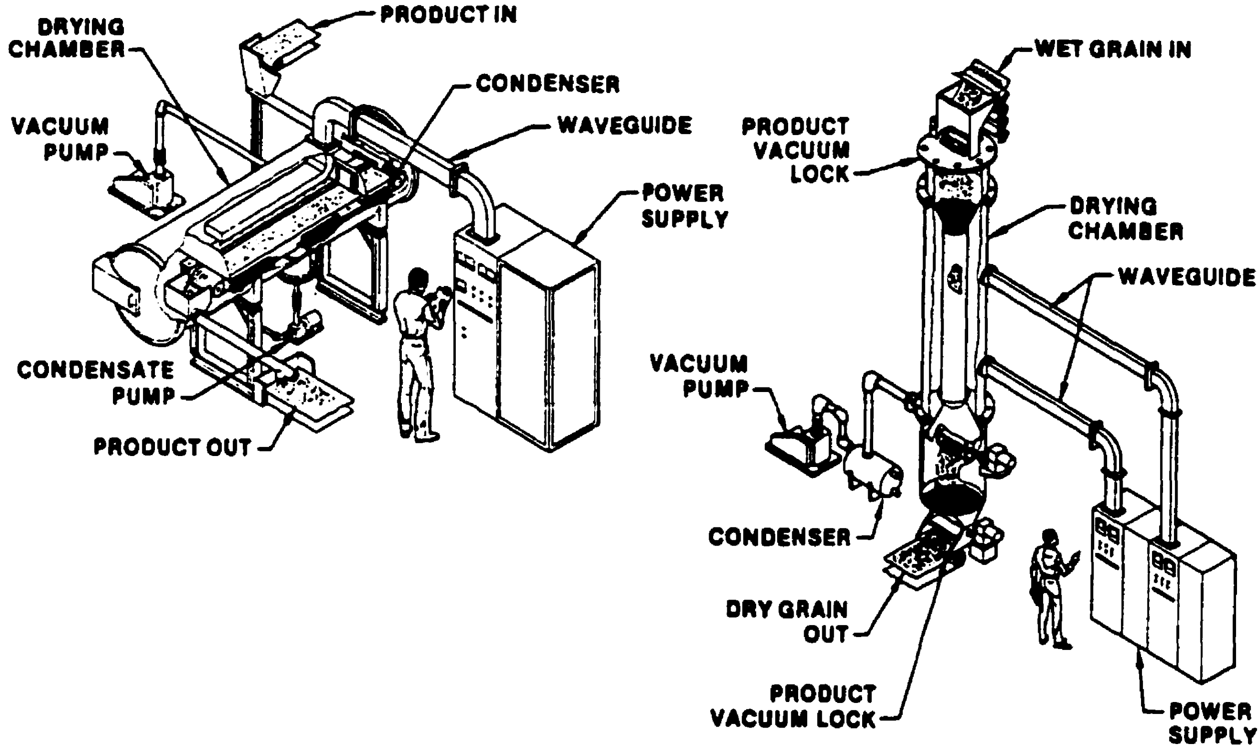

Figure 2.8 MIVAC Microwave Vacuum Dryer (McDonnell Aircraft Co. 1977).

The Ken Bratney Co. (1982) developed a full-scale continuous flow microwave grain dryer. The VAC-U-WAVE™ is available in two models; the VUW-2220, with a power consumption around 100 kW for a capacity of more than 12500 kg per hour, and the VUW-2420 with consumption of 200 kW and capacity of 25000 kg per hour. The system consists of a two-stage flighted auger circulating the grain in vacuum drying chambers subjected to microwave application by multiple magnetrons. Figure 2.9 shows a schematic of the 100 kW dryer with the flow path of the grain the other media well identified. The company reports bacteria kill at 105°F kernel temperature without loss of germination and no alteration to amino acids, food or feed value. The energy required to remove water was reported as well below 1165 kJ/kg. The company started manufacturing and marketing such dryers in 1982 especially for large grain processing facilities (see Figure 2.10).

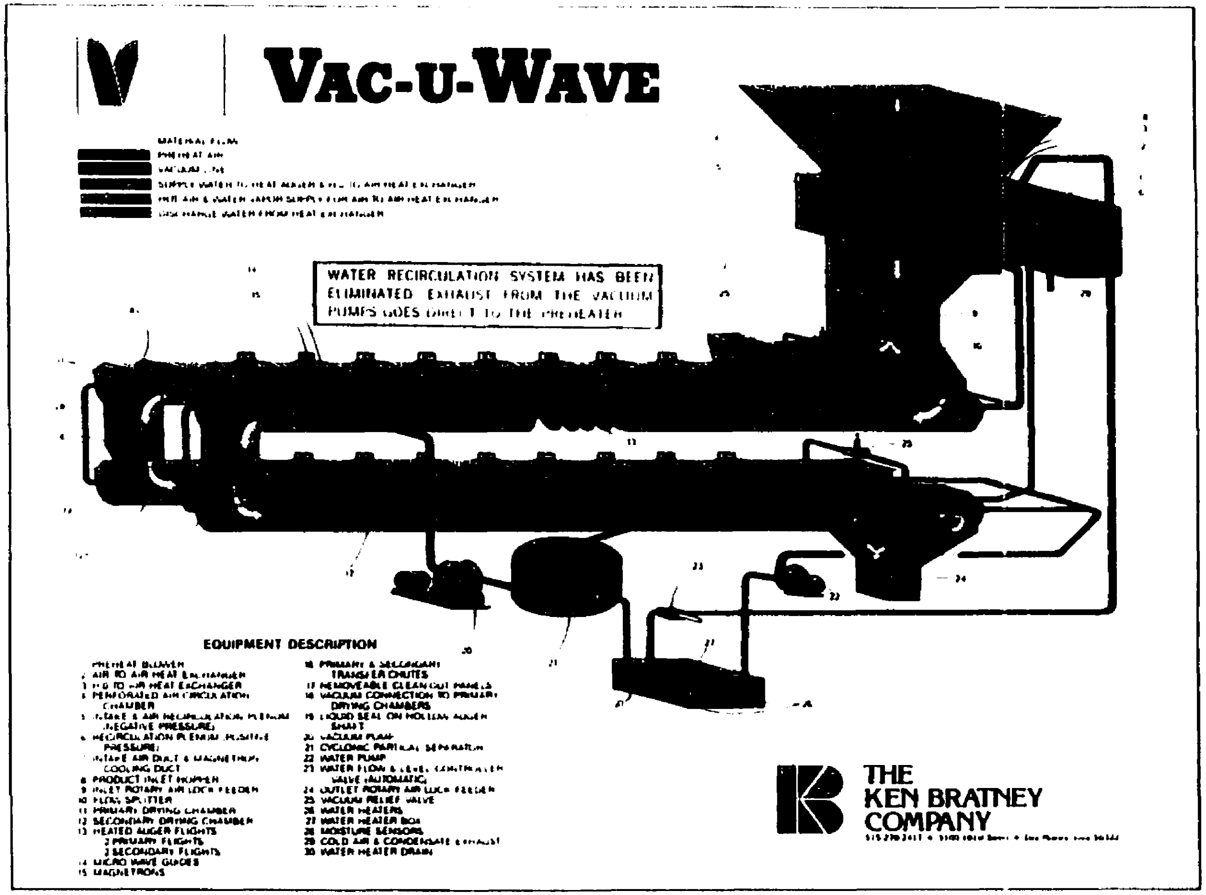

Figure 2.9 Schematic of a 100 kW grain dryer (The Ken Bratney Co, 1982)

The drying characteristics of corn in a microwave field with a surface-wave applicator were studied by Shivhare et al. (1991). The apparatus used is shown in Figure 2.11. A microwave generator operating at 2.45 GHz could produce variable output power levels in the 0 to 2.5 kW range. The power from the generator was transmitted through a rectangular waveguide to the surface wave applicator. Tuners, installed in the waveguide, facilitated the control of the reflected and incident microwave power to and from the generator. Heated air at 30°C and approximately 7% relative humidity was used to carry moisture from the grain bed. An inlet air velocity of 0.5 m/s was used throughout the experiment. The temperature of the outlet air was measured and taken as an indicator of the grain temperature. The drying trials were performed in batches and the sample holder consisted of a quartz tube 3.2 cm I.D., 3.4 cm O.D. and 1.03 m high. The weight of the sample was continuously monitored during the process to obtain the drying rates of the corn.

Preliminary trials on drying corn with microwave power revealed that the absorbed power should be below 1 W/g of wet grain. Therefore, the absorbed power levels used 0.25 W/g, 0.50 W/g and 0.75 W/g of wet sample. The authors reported that the drying rates increased with an increase in absorbed microwave power, but reaching similar values after 2 hours of drying independently of the power level. The temperature of the outgoing air was observed to increased with increased absorbed microwave power levels. Germination and bulk density of seed corn were affected by the magnitude and duration of application of the microwaves. A variable microwave power approach was also tested. It consisted of applying high levels of absorbed microwave power for fixed periods and the switching to lower levels for the rest of the drying duration. Considering energy requirements and quality of the end product, a constant absorbed microwave power level of 0.25 W/g of wet grain was found to be acceptable for drying seed quality corn, and a variable microwave power operation with a combination of 0.50 W/g for 1.5 hours and 0.25 W/g for 2.5 hours gave the best results for drying corn for food and animal feed. Similar experiments with constant microwave absorbed power levels showed that a change in inlet air temperature (30, 35 and 40 °C) did not affect the drying behaviour of corn. An increase in inlet air velocity to 0.8 m/s was found to increase the moisture of corn at any given instant during the drying process, thus slowing it down.

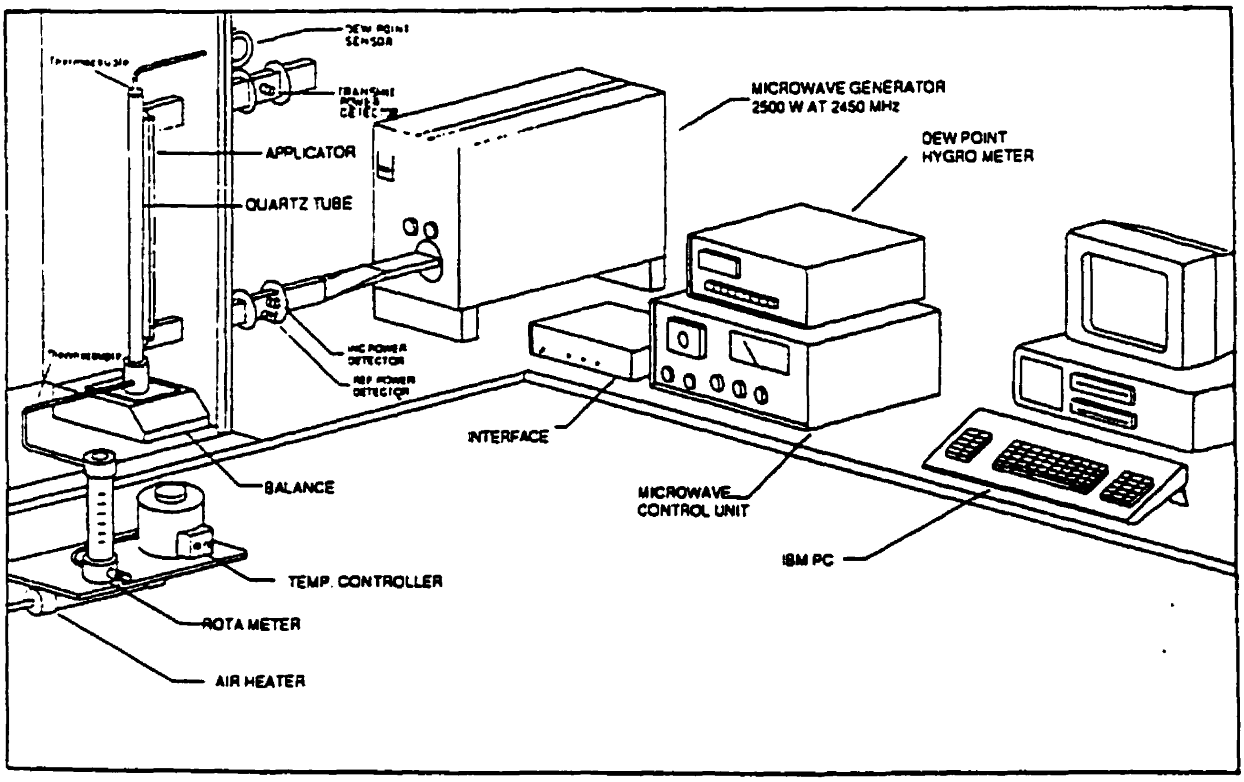

Figure 2.11 Schematic diagram of experimental setup for drying corn with a surface wave applicator (Shivhare, 1991).

2.4 Microwave applicators

A typical microwave heating and drying system is composed of three major group of components. At one end, the microwave generator supplies the electromagnetic waves at a fixed or variable power level. At the other end, the applicator is designed to couple this electromagnetic energy the most efficiently to the material to be heated, often referred to as the load. In between those two components, there must be several coupling devices to improve the transmission, or to protect the magnetron of the generator from reflected waves etc. Figure 2.12 is a sketch of a typical microwave heating and drying setup. The following section is concentrated on the theory and design of the applicator.

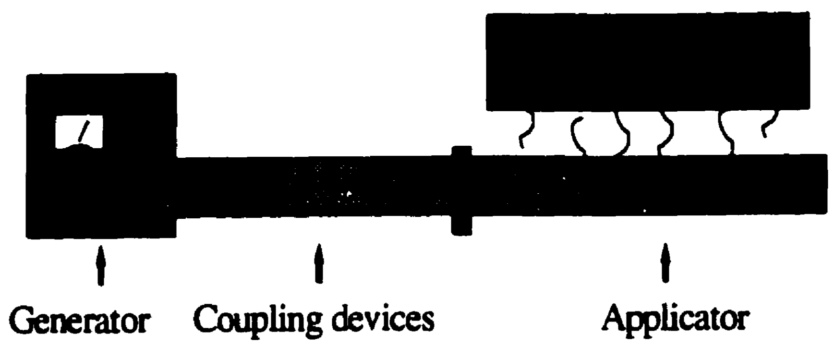

Figure 2.12 Typical microwave heating and drying setup.

2.4.1 The concept of travelling wave

It is known that a time-varying magnetic field produces a time-varying electric field (Faraday's law) which, in turn, produces a time-varying magnetic field (Ampere's law)... and so forth (Rizzi, 1988). Since one type field produces the other in a plane normal to it, the electric and magnetic fields are always perpendicular to each other and lie in a plane at right angle to the direction of propagation. This plane wave constitutes the simplest way in which electromagnetic energy can propagate. A simple method of describing this phenomenon is to put each field as a function of only one coordinate in 3-D. Figure 2.13 shows an electromagnetic wave at two different time in the 3-D coordinate system. This uniform plane wave is called a transverse electromagnetic (TEM) wave. By definition the plane is infinite requiring a generator of infinite power and in practice only an approximation to a plane wave is possible (Metaxas, 1983).

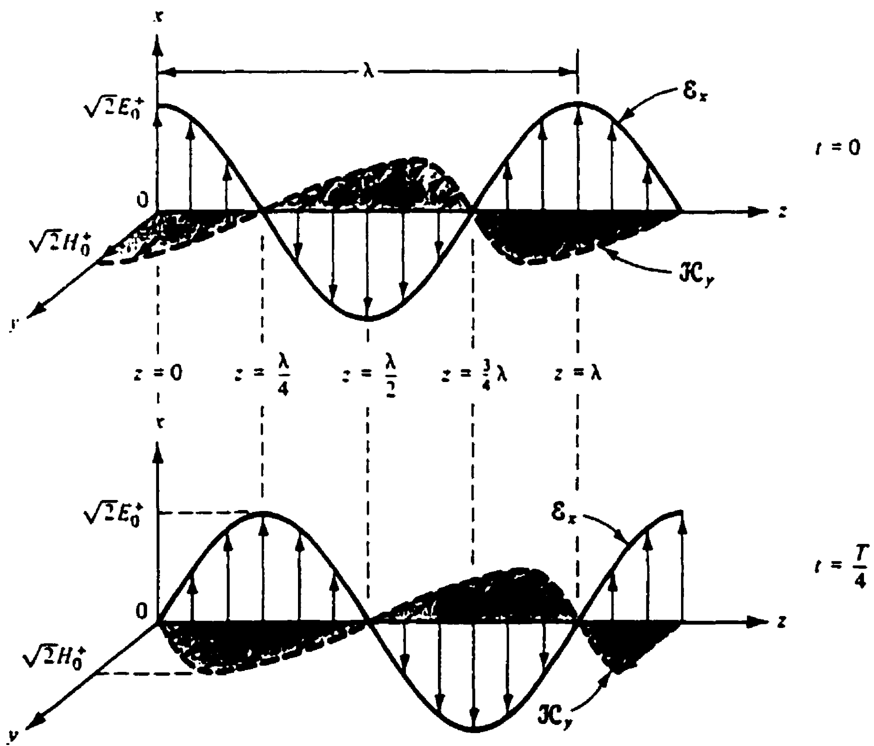

Figure 2.13 Description of an electromagnetic wave travelling in the positive z direction, shown at t = 0 and t = T/4 (Rizzi, 1988).

2.4.2 The concept of a guided wave

In addition to propagation in free space, microwaves can also be restricted to propagation inside vessels of precisely defined shape and dimensions. The coaxial waveguide, due to its two conducting layers separated by a dielectric material, can support the propagation of the transverse electromagnetic mode, with wavelength and speed of propagation identical to that of free space. Coaxial cables are quite extensively used for various purposes. The RF cables used to connect an antenna to a TV and /or video in most living room is one example of a coaxial cable. Similar cables can be used at microwave frequencies. A second means of propagating microwaves in restricted conduits consists of the monoconducting waveguide, which can have a circular or rectangular cross section.

(a) (b)

Figure 2.14 Cross section of coaxial (a) and rectangular (b) waveguides shown with the electric field vector (Bialod and Marchand, 1986).

Figure 2.14 shows the cross-sectional view of the coaxial and rectangular waveguides, which are the most widely used in industrial applications, the latter being the main point of interest of the present research. However, the rectangular waveguide cannot propagate the TEM mode. The plane wave propagation can follow the transverse magnetic (TM) or the transverse electric (TE) mode. The second capital letter designates which field has its direction always and everywhere transverse to the direction of wave propagation. The mode notation also includes three subscripts in the form TM_{mnk} or TE_{mnk}. The m represents the number of full cycles of transverse field variation in one revolution through 2 rad of dia. The n represents the number of zeros of the transverse field along the radial of a guide. The k stands for the number of repetitions of the T_{mnl} mode with the opposite phase of the field configurations in the axial direction.

In a rectangular waveguide, the waves propagate by reflection on the walls which results in the speed of the energy propagation along the longitudinal axis of the waveguide being slower than that of free space propagation (Bialod and Marchand, 1986). The guided wavelength along the axis of propagation is therefore longer than the free space wavelength. Moreover, the reflection of microwaves coming from an exterior source on the walls of the waveguide cannot take place if the free space wavelength is too large with respect to the dimensions of the waveguide cross section.

For given waveguide dimensions, the cutoff frequency consists of the lowest frequency at which the waves can propagate freely in the waveguide. There are several cutoff frequencies corresponding to different modes of propagation, but the careful choice of waveguide cross section can allow propagation exclusively in the simplest mode. It is then easier to evaluate the electric field in the waveguide as well as the line of currents on its walls. Figure 2.15 illustrates the electric and magnetic fields as well as the current lines for the simplest mode in a rectangular waveguide. There exists standard waveguide dimensions which have been calculated for minimal losses in the walls as shown in Table 2.1. However, one could make one's own waveguide as long as the material used is non-magnetic and the dimensions respect the criteria of the narrow side being smaller than a half-wavelength in free space and the broader side being larger than a half-wavelength in free space. The arrangement of a waveguide circuit for microwave propagation is commonly referred to as a transmission line.

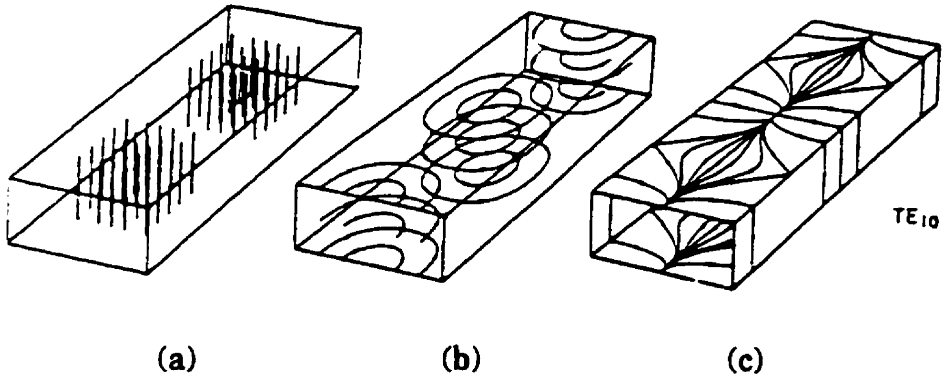

Figure 2.15 Rectangular waveguide with Electric field (a), Magnetic field (b) and lines of current (c) for the simplest mode of propagation (Bialod and Marchand, 1986).

In the case where this transmission line is terminated by a load with a certain impedance, a fraction of the incident waves are reflected. The ratio of the complex amplitudes of the reflected over incident waves is called the reflection coefficient. It can be readily measured because the forward and reflected waves add vectorially along the transmission line giving rise to a cyclical variation of the field intensity along the line, creating a standing wave (Metaxas and Meredith, 1983). The ratio of maximum to minimum value of the transverse electric field is called the standing wave ratio. It ranges from 1, for zero reflected power, to infinity, for a hundred percent reflected power.

Table 2.1: Characteristics of different waveguides for use at 2.45 GHz.

Type	Inside dimensions (mm)	Guided wavelength (mm)
WR-340	109.22 x 54.61	147.65
WR-341	86.36 x 43.18	173.30
WR-284	72.14 x 34.04	230.89

2.4.3 Travelling wave applicator

Travelling wave applicators are defined as microwave heating applicators in which power, fed into a chamber from the generator, is substantially absorbed by the workload with the residue being dissipated in an absorbing terminating load (Metaxas and Meredith, 1983). This type of applicator is usually configured in a continuous flow, often with a conveyor belt running through the middle of the broad side of the waveguide where the electric field is at its maximum value. It is more suitable for high loss materials, since the length required to heat a low loss material would be inconveniently long. The travelling wave applicator can be of the axial type, where the material travels along the longitudinal axis of the waveguide . In this case, there is a restriction on the width of the material, which should not exceed 3/8 λ_0. The second type of travelling wave applicator is the meander type, where the material travels at right angle to the length of the waveguide. In that case, a problem arises as the electric field is not constant over the width of the material, thus necessitating a multi-pass or meander applicator. (Fanslow and Pavlat, 1976) have used a conformal mapping approach in order to determine the field values inside the meander applicator.

2.4.4 Single mode resonant cavity

A single mode resonant cavity is a chamber with at least two dimensions being inferior to the wavelength. Usually, a resonant cavity is made of a portion of a waveguide shorted at the ends. It can either consist of a rectangular or a circular waveguide. The precise knowledge of electromagnetic field configuration enables the dielectric material under treatment to be placed in the position of maximum electric field for optimum transfer of electromagnetic energy to it. In such a system, the stored energy reaches a maximum when the microwave frequency in the circuit corresponds to the resonant frequency of the cavity. Metaxas (1974) has investigated the use of a resonant cavity as a heating device at 2.45 GHz. Tulasidas (1994) has used a single mode resonant cavity for drying grapes into raisins.

2.4.4.1 Cavity perturbation

When a small piece of dielectric material is introduced into a resonant cavity, the frequency of resonance is changed by a small amount as well as the quality factor Q of the cavity. These effects are commonly used in the measurement of the dielectric properties of the sample. The shift in resonance frequency is considered to be mainly affected by the dielectric constant while the change in the Q factor is associated to the dielectric loss. The Q factor consist in a quantification of the sharpness of the peak in the resonance curve. Thus, when an object is introduced in the cavity, the resonance frequency will decrease and the Q factor will be lowered, causing a broader, flatter resonance curve (Kraszewski and Nelson, 1994). In active cavity perturbation (ACP), the same principles apply for the determination of the dielectric properties from the shift in the resonant frequency and the change in Q. However, the operation of the system is mainly based on the information concerning the phase of the cavity rather than the frequency. An oscillation condition is produced whenever proper conditions of phase and amplitude are satisfied in the feedback loop (Akyel and Bosisio, 1990). This technique has been used to determine the dielectric properties of various agri-food materials including grains (Venkatesh, 1996).

2.4.5 Multimode oven applicator

The multimode oven applicator is also a cavity, but has at least two dimensions several wavelengths long. The household microwave oven falls in this category, which make it one of the most popular applicator for heating. It is mechanically simple and versatile in being able to accept a wide range of heating loads (Metaxas and Meredith, 1983). There is, however, a spatial non-uniform distribution of heating within a multimode oven which can be reduced by the addition of a mode stirrer, or by moving the load inside the cavity. Because of its characteristics, the multimode oven is not quite compatible to continuous flow processes.

2.4.6 Slotted waveguide applicator

The slotted waveguide is one example of a versatile applicator since it can be used as a travelling wave applicator, when the line is terminated by a matched impedance, or as a standing wave applicator, when the line is terminated by a short circuit. The basic principles of this radiating equipment are well explained in literature (Johnson and Jasik, 1984). A slot cut in the broad side of a rectangular waveguide, in a transverse direction to the current lines, produces a significant perturbation of the current array with the result that the internal field is coupled to space. A slot of this type constitutes a radiating element. The degree of energy coupling depends on the current density intercepted by the slots and their location on the waveguide. A slot lying along the centerline of the broad face of the guide produces only a minor perturbation of the current distribution and therefore, radiates very little. However, an increased coupling of the internal field is obtained when the slot is either cut at a certain distance from the centerline or rotated to a certain degree with respect to the centerline. Figure 2.16 shows the longitudinal shunt slots or inclined series slots cut in the broad side of a waveguide.

It is well established in literature that these radiating elements must correspond to certain basic characteristics among which, the following: The length of each slot is equal to $\lambda_o/2$. All slots are spaced $\lambda_g/2$ away from each other. Adjacent slots are placed symmetrically opposite with respect to the centerline for longitudinal shunt slots and inclined in the opposite direction across the wall centerline for inclined series slots, which causes all slots in the array to radiate in phase. A short circuit (when required) is achieved in a plane (approximately) at $\lambda_g/2$ past the last slot in the array, ensuring that standing wave voltage minima appear at all slot positions.

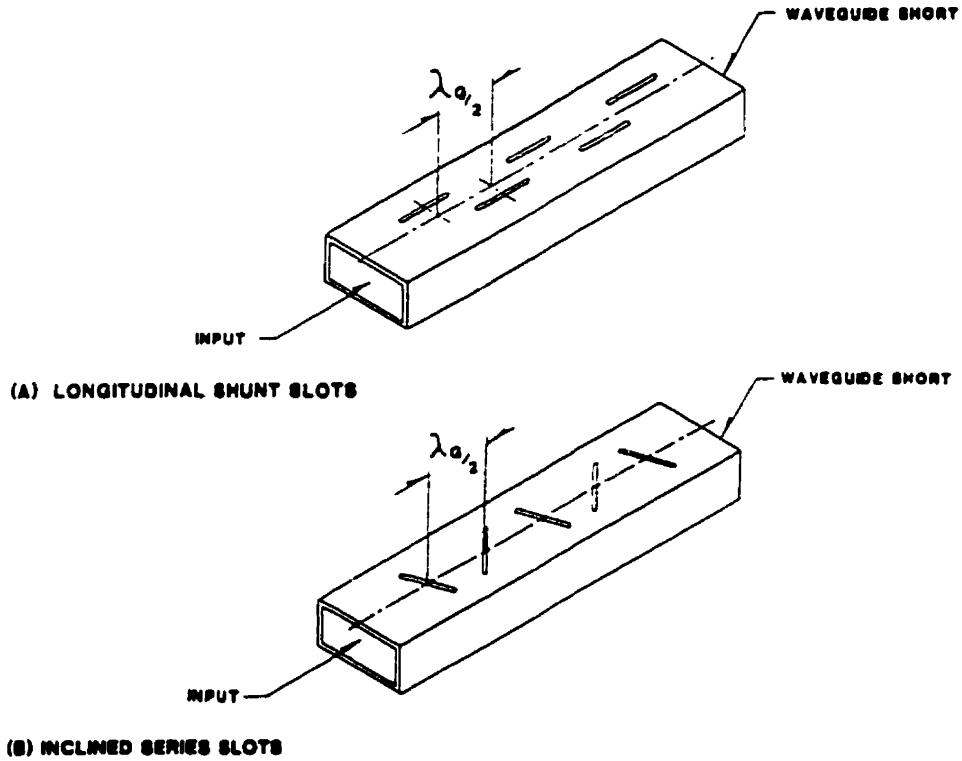

Figure 2.16 Basic waveguide slot arrangements (Ji and Gerling, 1988).

These examples of radiating slots have been examined by Ji and Gerling (1988) for their potential use on applicators for the introduction of microwave energy into a plasma chamber. The tests were performed at low power with the applicator radiating in free space. The best results were obtained with a setup consisting of five inclined series slots at an inclination of 75° . Sauvé et al. (1993) tested the same apparatus under low and high power and reported an efficient transfer of the microwave power to the plasma and a good axial uniformity of the discharge at high power.

For the inclined series slots, the radiation resistance at resonance is determined by the inclination angle ∅ of the slot with respect to waveguide wall centerline. It increases monotonically with increasing ∅, from zero for ∅ = 0° (non radiating longitudinal slot) to a maximum value for ∅ = 90° (transverse slot). For a given impedance of the total load, each series slot represents a fraction of the total impedance. Their inclination must be equal and apposite for adjacent slots so that they all have the same radiation resistance. Moreover, the number of slots can be changed, but an increase in the number of slots should result in a decrease in the slot inclination angle ∅ so that the sum of all slots radiation resistance remains constant (Sauvé et al., 1993).

III MATERIALS AND METHODS

Most of the fabrication of the experimental equipment required in the present work has taken place at the Agricultural Engineering shop of the Agricultural and Biosystems Engineering department of McGill University, Ste-Anne-de-Bellevue (Québec). The preparation, rewetting and moisture content analysis of the corn also took place in these premises. All microwave measurements were however performed at the research facilities of POLY-GRAMES, École Polytechnique, Montréal (Québec) due to a joint research project with Dr. Cevdet Akyel, member of POLY-GRAMES, who also supplied the equipment used for that purpose.

3.1 Special waveguide antenna

The basis of the present work lies in the fabrication of a special waveguide antenna which can allow modifications of its design parameters without having to rebuild it for each combination. The antenna falls in the category of a slotted waveguide with series slots cut on the broad side as described in the previous chapter. However, one of the parameters to be investigated required that the angle of slot inclination with respect to the longitudinal axis of the waveguide be varied to verify its effect on the radiation characteristics of the antenna. The solution adopted consisted of piercing the slots in discs that would themselves be removable from the body of the waveguide. These discs could be rotated to change the slot inclination angle $\varnothing$ or replaced by discs with other slot shapes if desired. The selected frequency for the operation of the equipment was 2.45 GHz due to availability of equipment and the popularity of that frequency in industrial microwave heating and drying applications.

As seen previously, the frequency of the alternating electromagnetic field has an effect on the size of the waveguide to be used. Before selecting which of the waveguide listed in Table 2.1 would be used, the length of the slots had to be specified. The theory found in literature suggests the length of the slots to be in the neighbourhood of $\lambda_g/2$ which corresponds to 61 mm at 2.45 GHz. Bialod and Marchand (1986) have suggested a length of 57.7 mm based on theoretical calculations for industrial applications with configurations similar to the present work. For that reason, a slot length of 57.7 mm was adopted and a slot width of 6 mm was retained in order to be consistent with the values found in literature. The next parameter to consider was the distance between two consecutive slots, which, in theory should correspond to $\lambda_g/2$, a value also used in industrial applications (Bialod and Marchand, 1986). Knowing this information, the choice of the particular waveguide to be used, relied on the possibility of having slots as close as possible to each other, for more uniform radiation, while physically permitting to rotate them. The WR-430 (see Table 2.1) was eliminated first due to the distance between slots (73.82 mm), which wouldn't permit enough material thickness on the walls of both the disc and the waveguide. The WR-340 was selected among the remaining two models for the proximity of the slots (86.65 mm) compared to 115.44 mm for the WR-284. The WR-340 is a standard often used especially in European countries whereas the WR-284 is mostly found in North-America. All three models described above are usually made of copper, a very good conductor.

The next parameter to consider was the effective length of the antenna. The number of slots (12) was selected so that the radiation pattern of the antenna would cover sligthly more than 1 m (1.039 m). The total length of the waveguide had to be compatible with the eventual use of a short-circuit at one end. The short circuit consists of a plate perpendicular to the longitudinal axis of the waveguide which reflects the wave and helps tune the system for desired standing wave pattern when desired. It can be a movable short-circuit for ease of adjustment, and its position should be around $\lambda_g/2$ past the last slot in the array. Knowing the flanges used for WR-340 to be 3/8" thick (9.52 mm), the total length of the waveguide was set at 1194 mm so that the movable plate could easily be placed at a distance close to 86.65 mm from the last slot.

Thus, twelve holes of 70 mm diameter were cut through the 2 mm wall on one broad side of the waveguide to accept the slotted discs. In order to adjust precisely the slot inclination angle, the outer wall of the waveguide was graduated radially at each slot location between 0° and 90° with steps of 15°. The perimeter of a disc had a mark perpendicular to the slot length in order to obtain the desired inclination. A good surface contact between the discs and the wall of the waveguide is crucial for microwave propagation and thus was achieved by taps, four screws per disc tightened around the perimeter. Metal screws (size 8-32), cut at the right length to prevent them from exceeding the inner surface of the guide's wall, were used for that purpose. The actual characteristics of the waveguide antenna are listed in Table 3.1.

Table 3.1: Characteristics of the antenna.

Parameter	Value
Model	WR-340
Guided wavelength	86.65 mm
Inside dimensions	86.36 x 43.18 mm
Wall thickness	2 mm
Total length	1194 mm
Diameter of holes	70 mm
Distance between successive holes	86.65 mm
Distance from last hole to end	77.1 mm

A first set of slotted discs was made at the same time as the modified waveguide. It consisted of aluminum plates 3/16" (4.75 mm) thick machined to a 80 mm dia. with a 2 mm deep, 70 mm dia. seat to match perfectly the holes on the waveguide. The design tolerance was 0.3 mm on the diameter. Aluminum is a valid material with conducting properties similar to those of copper for microwave applications. The slots were centered in the discs and were 6 mm wide by 57.7 mm long with rounded corners and rounded bottom edge. Figure 3.1 shows one aluminum slotted disc viewed from below. A sketch of a portion of the antenna with the aluminum discs in place is found in Figure 3.2. The slotted discs were numbered from 1 to 12 as well as their location on the waveguide and this order was respected for all experiments.

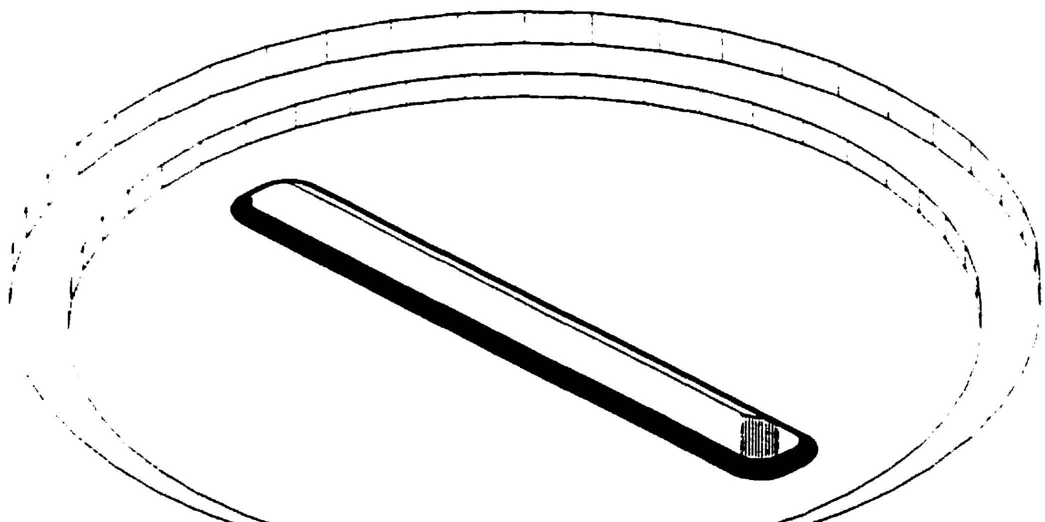

Figure 3.1. Aluminum slotted disc viewed from below.

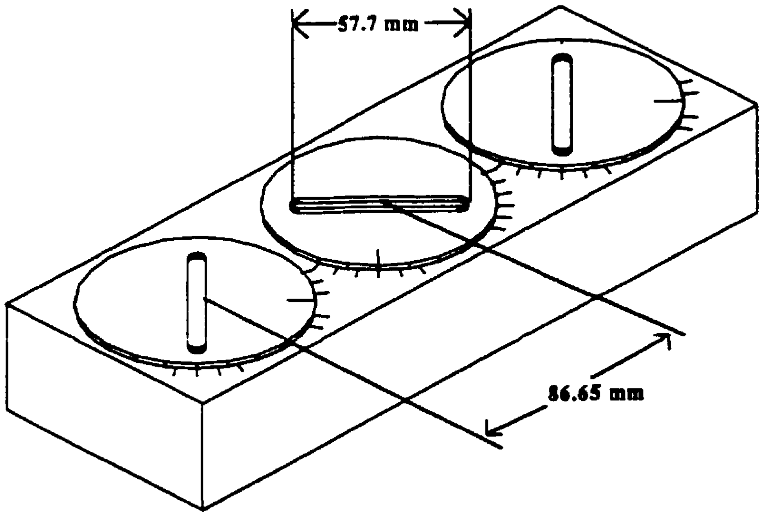

Figure 3.2 Details of the adjustable discs with graduation for angular positioning.

3.2 Preliminary trials

Sets of preliminary trials were undertaken to give a first idea on the performance of the antenna. The test involved small values of microwave power in the range of milliwatts and is usually referred to as a reflectometry test. The appropriate equipment was used to obtain the fraction of incident power that was reflected and transmitted. Figure 3.3 illustrates these parameters in terms of microwave reflectometry. The bases for this concept are similar to those which governs the behaviour of electromagnetic waves in the visible range such as light. For a given incident power, a portion of the wave is reflected back to the incoming direction (reflected power) while another portion is transmitted through (transmitted power). By measuring these three values, it is possible to obtain the absorbed power ie. the rate at which electromagnetic energy is coupled to the environment or surrounding material.

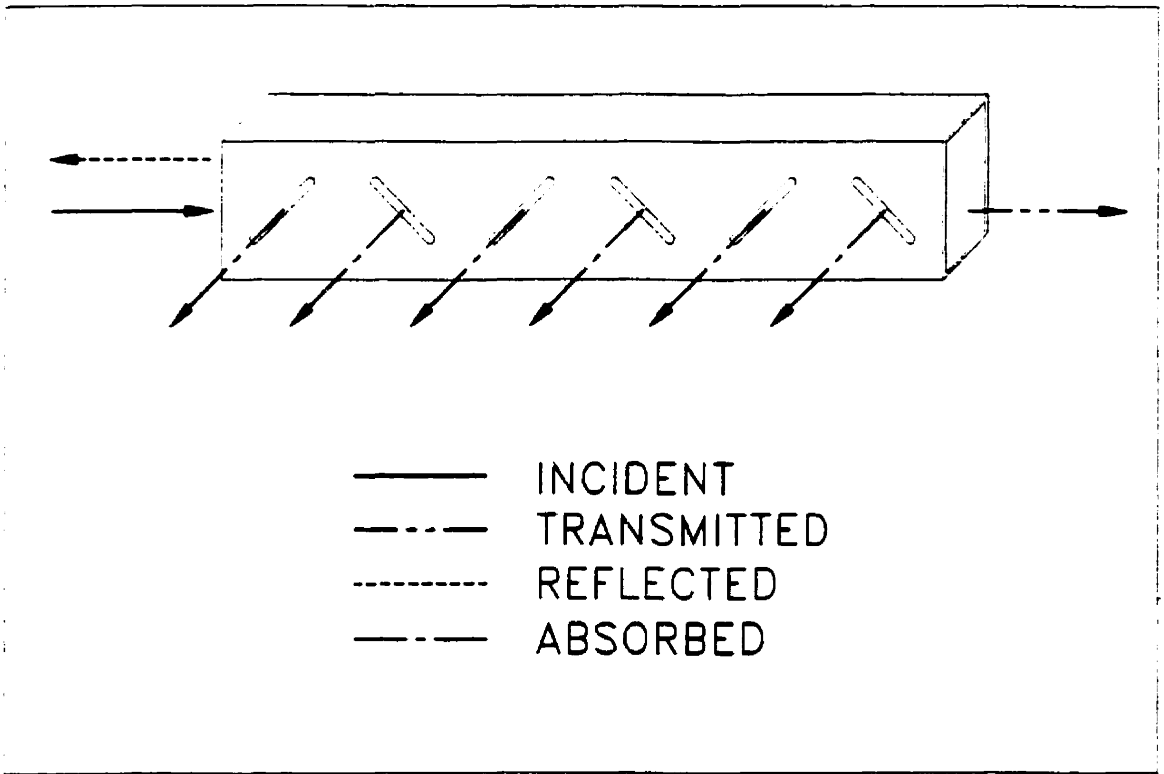

Figure 3.3 Schematic of the incident, transmitted, reflected and absorbed power patterns for a slotted waveguide applicator.

The absolute values of microwave power can be related by the following equation:

$$|Pi| = |Pr| + |Pt| + |Pa| \tag{3.1}$$

where:

Pi = Incident power (W)

Pr = Reflected power (W)

Pt = Transmitted power (W)

Pa = Absorbed power (W)

A first set of experiments consisted of a study of the radiation characteritics of the antenna with all the aluminum discs in place for different combinations of Ø and radiation load. The results obtained for these trials were not as good as expected and are discussed in Chapter IV. For that reason, a second set of preliminary tests was conducted with various slot shapes. However, this time, due to uncertainty with the results, the discs were fabricated from brass shim sheets of 0.005" (0.127 mm) thickness. The use of this material facilitated the fabrication of these discs much faster and simpler. One of the drawbacks however, is the discontinuity obtained on the inner surface of the waveguide wall due to the lack of a machined profile that sits in the hole. At that time, the hypothesis was that the original aluminum slots could be reworked in the shape of the most successful of the second generation slots.

At this point, it is essential to introduce specific names to the different shapes of slots. The original aluminum slots will be referred to Type 1 slots, whereas four other shapes were made of brass sheets, namely Types 2 to 5. In order to hold the brass discs in place, rings made of aluminum were fabricated with the appropriate dimensions and fixed to them. The perimeter of the aluminum ring was marked for graduation of the inclination angle. Three copies of each type of second generation discs were made in this fashion. The top view of all the disc shapes tested is found in Figure 3.4.

3.2.1 Experimental setup

The experimental setup used for preliminary experiments was composed of an HP8410A network analyzer combined with an HP8412A phase magnitude display. A sweep oscillator HP8690B supplied the signal to the phase magnitude display and an HP8742A reflection test unit, which was itself connected to one end of the antenna and an HP8411 harmonic frequency converter. The reflection signal incoming from the antenna was carried back from the harmonic frequency converter to the input of the network analyzer. At the other end of the antenna, an HP8482 power sensor was connected to an HP436A power meter to monitor the transmitted signal. The signal was carried by coaxial cables to and from coax to WR248 adapters which were themselves connected to the antenna via WR-284 to WR-340 adapters. The incident signal is always entering the antenna at slot number 1. The power of the signal was measured in dBm, which can ultimately be tranformed to absolute values knowing the reference point.

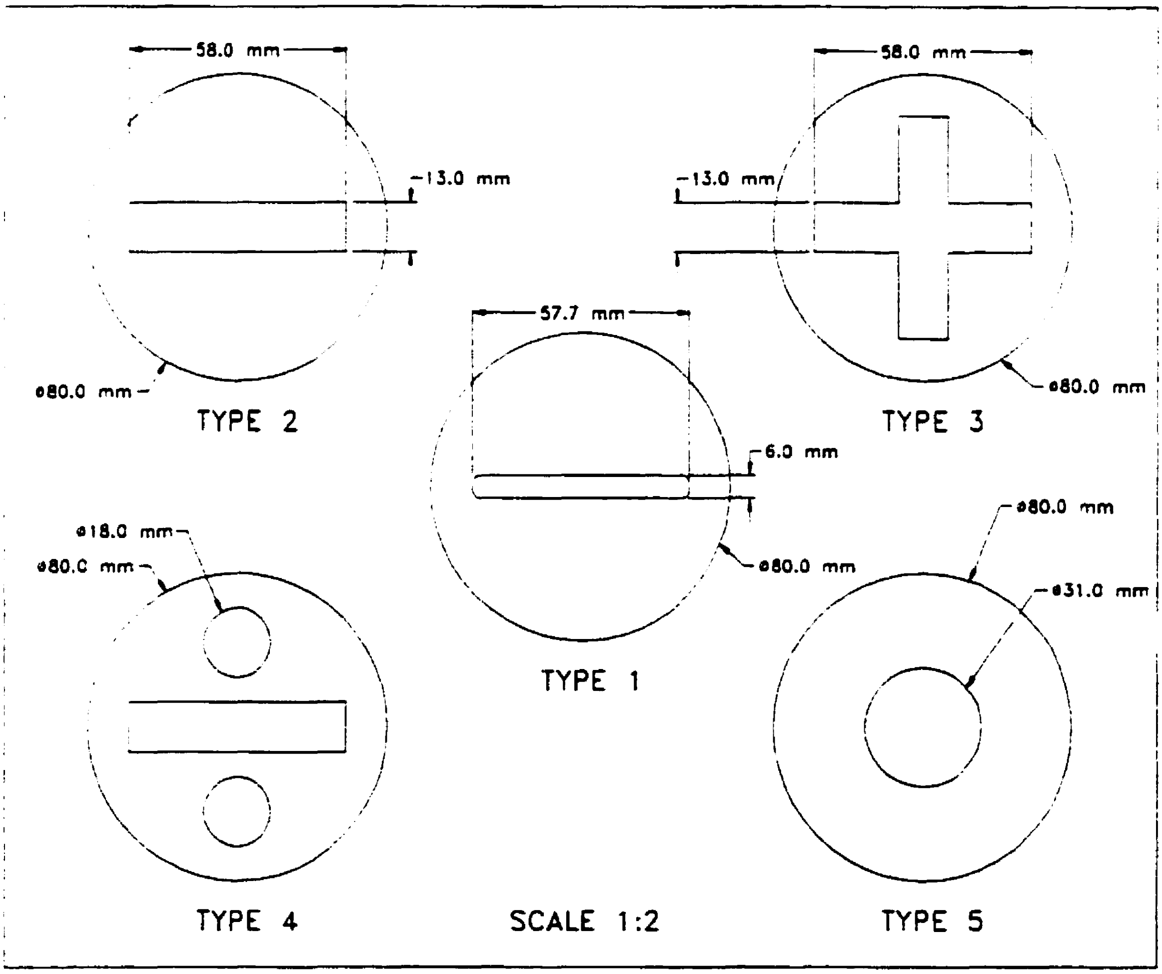

Figure 3.4 Types of slotted discs used throughout the experiment.

3.2.2 Procedures

As explained earlier, there were two sets of experiments. The first involved the use of 12 discs of type 1. The experimental design is as shown in Table 3.2. The slot inclination angle ∅ was varied from 0° to 180° in steps of 15°. Consecutive slots were inclined in opposite directions for reasons explained earlier. This resulted in a duplication of the slot array patterns, since past 90°, every step presents an array symmetrically opposite to its conjugate below 90°. As expected, the radiation patterns obtained between 0° and 90° were found to be very similar to their counterparts between 90° and 180° for all inclination angles. Therefore, it was decided to use only one side of possible inclination and keep the same side throughout the whole project for the sake of comparisons. That is, with the operator looking down on the antenna, slot number one is on the left and can be oriented from 0° to 90° as usually represented in a Cartesian coordinate system. This is illustrated in Figure 3.5 where slot number one is at angle 75°. The other parameters under investigation in the first preliminary experiment were related to the environment surrounding the antenna. One set of measurements was taken with the antenna radiating in free space. Then a Teflon™ tray was added on top of the antenna at different heights from the top surface of the discs (air gap) and with or without a water load on top of the Teflon™ tray.

Table 3.2: Experimental plan for first preliminary trial.

Parameter	Levels	Description
Slot inclination angle	7	0°, 15°, 30°, 45°, 60°,75° et 90
Type of slotted discs used	1	Type 1
Load characteristics	3*	Free space, Teflon tray alone, Teflon tray with water load
Position of load (air gap)	3	0, 0.5 and 1.5 cm

* free space is a special case without different position of load

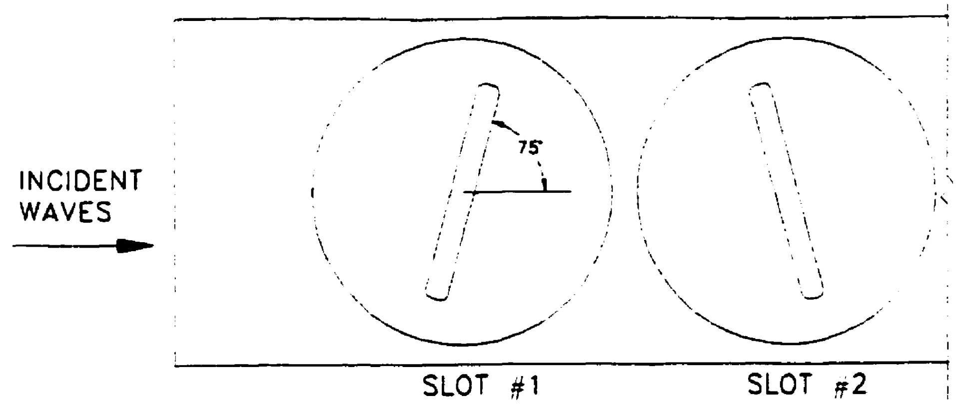

Figure 3.5 Waveguide antenna with adjustable slots at 75°.

The second set of experiments used only slots number one to three. The other slots were covered on the inside wall by aluminum tape and left in place at an angle of zero. Again, Ø was varied between 0° and 90° in steps of 15°. The other parameters examined were of the same nature as those of the first trial, with a few variations as listed in Table 3.3. The results are discussed in chapter IV and led to the development of the following experimentation.

Table 3.3: Experimental plan for second preliminary trial.

Parameter	Levels	Description
Slot inclination angle	7	0°, 15°, 30°, 45°, 60°, 75° and 90°
Type of slotted discs used	5	Type 1 to 5
Load characteristics	3*	Free space, Teflon tray alone, Teflon tray with water load
Position of load (air gap)	2	0.8 and 1.5 cm

* free space is a special case without different position of load

3.3 Corn drying simulation experiments

Following the preliminary test results, it was decided to make a whole set of type 2 discs which could be used in an experiment including the presence of corn in the surrounding of the antenna. These additional discs were fabricated with the same characteristics as the three existing discs. However, additional hardware was added with the idea of simulating the conditions which could be found during eventual high power operation of the antenna. As stated previously, the focus is kept on developing equipment which would be compatible with the existing grain conveying and drying facilities. Reducing the size of the dryer or the amount of moisture to be removed are expected to be solutions to the equipment cost problems. A combination of microwave with conventional drying methods accomplishing the bulk of the drying task might be desirable.

Actual grain drying and storage facilities often use grain moving equipment in which the material travels in a closed cylindrical tube. It is the same for screw and pneumatic conveyors as well as gravity flow from bucket elevators. One could imagine that the microwave applicator could be implemented on the walls of the conveying tube to obtain a continuous flow heating and drying while transporting the grain between two ends of the processing plant. Eventually, the system should be implemented with adequate means of wave leakage prevention while maintaining the use of hot or ambient air as a moisture carrier should be considered.

With these considerations in mind, a more evolved setup was constructed. A shield with octagonal shape was built to form a cavity for microwave reflection and confinement. The shield was designed to allow a Pyrex™ tube with 90 mm I.D. and 2.5 mm wall thickness to run across the cavity, in the center axis of the octagon, parallel to the waveguide wall. The tube was available at a length of 123 cm which was consistent with the requirement of exceeding the effective length of the antenna. Each side of the octagon has a width equal to the exterior dimensions of the broad side of the waveguide and the total length of the shield is 111 cm. The octagonal shape was adopted because it simulates well the eventual shape of the cavity with additional waveguide antennae in place at right angle to each other as shown in Figure 3.6.

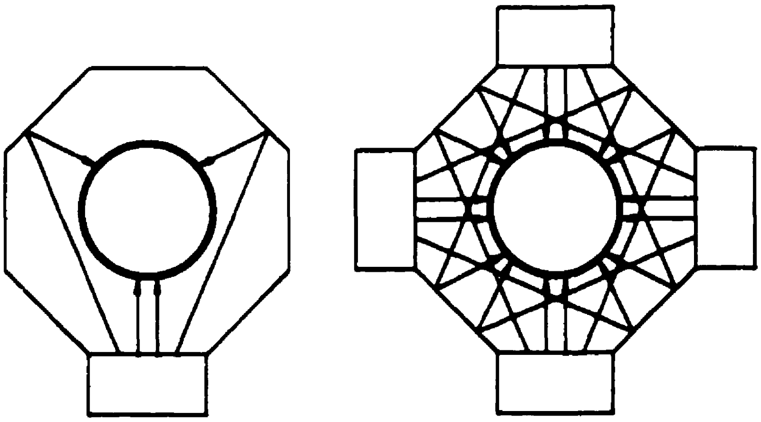

Figure 3.6 Cross section of the shielded setup in actual configuration (left) and projected quadruple waveguide configuration (right) with wave reflection patterns.

This configuration was considered as a potential layout for the completed dryer. The Pyrex™ tube was selected due to its low cost and resistance to high temperatures while presenting acceptable permeability to the microwaves. Its diameter is not identical to what is found in grain moving equipment where a diameter of 152 mm is very popular. However, it is consistent with the penetration depth of bulk corn, for which a minimum value of slightly more than 5 cm can be expected at 2.45 GHz (Shivhare, 1991).

A special holder was designed in order to fix the shield to the waveguide antenna with a good surface contact while allowing for simple and fast removal for adjustment of the slot angle. For each experimental unit, a Teflon™ tube 38 mm O.D. by 6 mm wall thickness was inserted along the center axis of the Pyrex™ tube in order to create an air pocket in the middle of the material. This shaft could serve as a stirrer or a flighted auger in a complete dryer setup. It could also be a good alternative to serve as the air flow conduit for evacuation of the moist air.

3.3.1 Experimental setup

The sensing equipment used for measurements during the simulation experiment was much simpler to handle than the equipment used in preliminary trials. An HP8753 network analyzer replaced the more complicated setup described earlier. The test ports of the network analyzer were connected directly to the antenna through various adapters (coax to WR-284 and WR-284 to WR-340). The network analyzer was calibrated with the short circuit and matched load provided by the manufacturer at the beginning of each run of experiment. The two test ports of the analyzer are named port one and port two, and it is crucial to know which one is which in order to differentiate reflection from transmission. During reflectometry measurements, the analyzer displays S_{11} and S_{21}, respectively corresponding to reflection and transmission (in dB), at a target frequency of 2.45 GHz and at frequencies of 2.425 and 2.475 GHz corresponding to a sweep of plus and minus 25 MHz . The terminology used is simple. S_{11} represents the fraction of a signal sent by test port one, which comes back through test port one in dB. Similarly, S_{21} represents the fraction of a signal sent by test port one which is received through test port two in dB. If desired, the display of the analyzer can also show S_{22} and S_{12}, in order to verify that the antenna presents similar behaviour in both direction of wave propagation.

3.3.2 Experimental design

The preliminary experiments have pointed out that the optimum slot inclination angle is often found to be in the 30° to 60° range, where a compromise between reflection and transmission is obtained. It was also pointed out that the type 2 slotted discs were more successful than the type 1 discs while presenting a relatively simple design. The effect of the presence of corn is also a factor which needs to be investigated.

With these considerations in mind, an experimental design was developed for the present study. It consists of studying the radiation characteristics of the antenna with six levels of slot inclination angle varying from 25° to 75° by increments of 10°, three levels of corn moisture content (15%, 24% and 32% w.b.), for both type one and type two slot shapes. This information is also listed in table 3.4.

Table 3.4: Experimental plan for corn drying simulation experiment

Parameter	Levels	Description
Slot inclination angle	6	25°, 35°, 45°,55°,65° and 75°
Type of slotted discs used	2	Type 1 and 2
Moisture Content of corn (w.b.)	3	15%, 24% and 32%

All measurements done with 3 replicates

3.3.3 Material preparation

Clean yellow-dent field corn (*Zea mays L.*) of the variety Funk™ 4120 was used throughout the experiments. The corn was harvested in October 1995 at the Macdonald Campus farm in Ste-Anne-de-Bellevue, (Québec). The harvest moisture content of the corn was around 24% (w.b.). The sample size required to fill the Pyrex™ tube was estimated to have a volume of around 7 liters, corresponding to roughly 5 kg. In order to insure a minimum of randomization in the sampling, the batch size was determined to be 25 kg, representing a population five times larger than the sample size. This value is small, but the volumes involved in this experiment didn't allow for larger batches due to restrictions in transportation to and from the measurement lab.

After harvest, a batch of 25 kg was immediately stored in a food grade container at 4 ± 1°C. A batch of 25 kg of corn was dried in a modified clothes dryer to lower its moisture content to a value around 14 % (w.b.). A third batch of 25 kg was remoistened to an expected 30 % m.c. (w.b.) using a modified cement batch mixer. The monitoring of moisture content throughout the drying and rewetting processes was achieved by measuring the weight of 75 kernel samples. The dry matter content of 75 kernels had already been established for the corn at 24 % m.c. and served as a reference point. After the desired estimated moisture contents were obtained, all batches were put in food grade containers and stored at 4 ± 1°C. The containers were agitated every 2nd day for one week and once a week for the following period. The moisture content of the corn on a wet basis was determined using the standard ASAE method (1994) by drying triplicate samples of approximately 15 g at 103 ± 1°C for 72 h in an air oven. It was measured shortly after reconditioning and after one week in he refrigerator. The exact values turned out to be 15, 24 and 32% m.c. (w.b.)

3.3.4 Procedure

The corn batches were taken out of the refrigerated environment and kept overnight at ambient temperature prior to sets of measurements. For each combination of slot angle ∅, moisture content and slot type, three replicate measurements were performed. The most complicated parameter to change was the type of slots. For that reason, the experiment was split in two with respect to the type of slots. The replicates were performed in consecutive batches, thus all measurements were done for replicate one, followed by those of replicate two and then replicate three. The combinations of ∅ and moisture content were tested in a random order for each replicate of each type of slot.

If only the moisture content had to be changed between two consecutive experimental units, the Pyrex™ tube was removed from the shield and the corn put back in the corresponding container. Then, the next corn sample was taken randomly from the corresponding container, and poured in the Pyrex™ tube with one end capped and the Teflon™ rod in place. The second end of the tube was then capped and the corn sample tube put back in the shield. If only the value of ∅ had to be changed between consecutive measurements, the shield and sample tube were removed; then the slots were adjusted and the sample tube put back in place for the next measurement. If both parameters had to be changed, the procedure was a combination of the two procedures described above. For each experimental unit, the values of S_{11} and S_{21} were obtained from the screen of the network analyzer. The values of S_{22} and S_{12} were consulted regularly, and they showed quite similar behaviour throughout the experiments and were therefore not recorded. Figures 3.7 to 3.10 illustrate the equipment at various stages between two measurements.

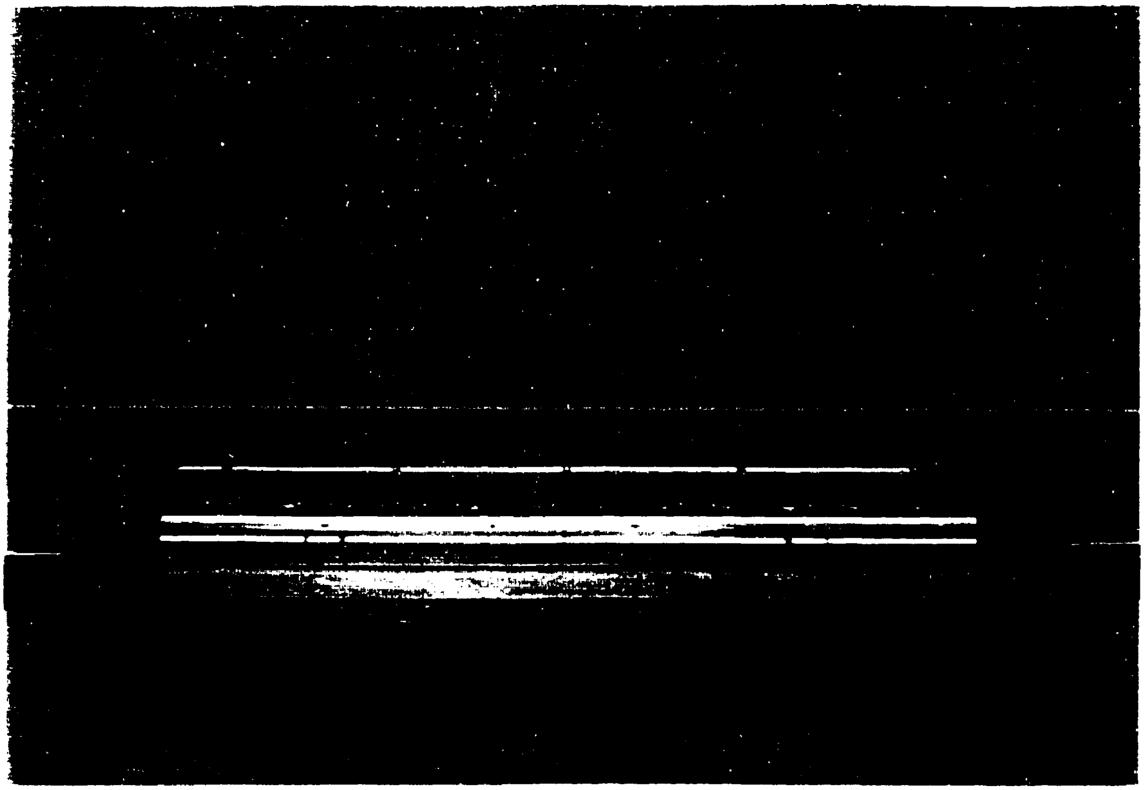

Figure 3.9 The antenna in its holder with type 1 slotted discs.

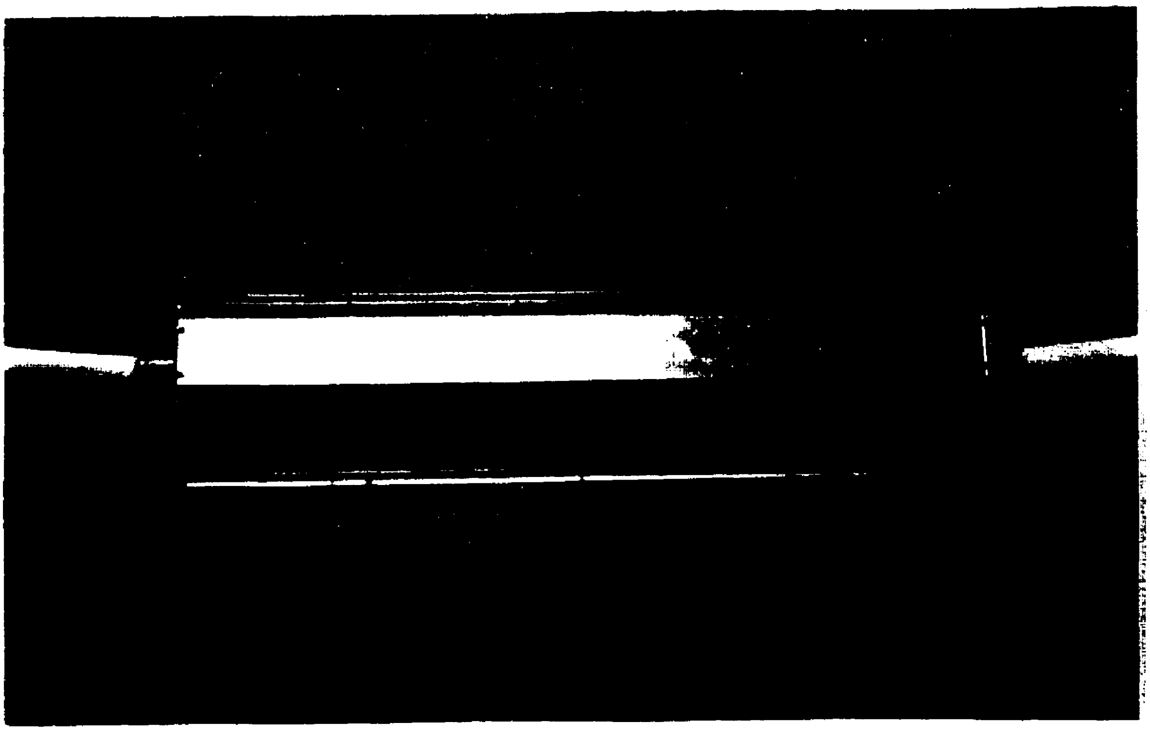

Figure 3.10 The antenna with sample tube and shield in place.

3.3.5 Moisture content monitoring

During the first part of the experiment corresponding to the type one slots, a 15 g sub sample of each corn experimental unit was withdrawn after the measurement was done. These sub samples were kept in sealed bottles until moisture content analyses were performed according to the previously stated method. This procedure was adopted in order to verify the effect of time on the corn moisture content at room temperature and to make sure that the higher moisture corn did not dry due to exposition to ambient temperatures during the experiment.

IV RESULTS AND DISCUSSIONS

4.1 Preliminary trials

The data obtained during the preliminary trials was in the form of dBm, for parameters such as Pi, Pr and Pt. Knowing these values, a simple calculation could give the value of Pa, the absorbed power following equation 3.1. The results are expressed in fractions of reflected power to incident power, Pr/Pi, transmitted power to incident power Pt/Pi and absorbed power to incident power Pa/Pi.

4.1.1 Antenna with 12 aluminum discs

The first preliminary experiment consisted of a study of the radiation characteritics of the antenna with all the aluminum discs in place for different combinations of ∅ and radiation load. The slot inclination angle was varied between 0° and 180° as stated earlier, but the values obtained between 90° and 180° were redundant and therefore only the values between 0° and 90° were analyzed. The other parameters under investigation in the first preliminary experiment were related to the environment surrounding the antenna. One set of measurements was taken with the antenna radiating in free space. Then a Teflon™ tray was added on top of the antenna at different heights from the top surface of the discs (air gap) and with or without a water load on top of the Teflon™ tray.

The results for the free space radiation are listed in Table 4.1 and those obtained with the addition of water on a Teflon™ tray 1.5 cm above the antenna are listed in Table 4.2 as examples. The complete results are listed in Table A1 of Appendix I.

Table 4.1: Radiation parameters for first preliminary experiment under radiation in free space conditions.

Slot Angle (°)	transmitted	Fraction of power reflected	absorbed
0	0.87	0.07	0.06
15	0.36	0.17	0.47
30	0.08	0.40	0.53
45	0.03	0.50	0.47
60	0.02	0.52	0.46
75	0.01	0.50	0.49
90	0.01	0.40	0.59

Table 4.2: Radiation parameters for first preliminary experiment with a load at 1.5 cm above the antenna.

Slot Angle (°)	transmitted	Fraction of power reflected	absorbed
0	0.89	0.07	0.04
15	0.38	0.23	0.39
30	0.10	0.50	0.40
45	0.05	0.47	0.48
60	0.03	0.59	0.38
75	0.03	0.59	0.38
90	0.03	0.50	0.47

In general, it can be observed that Pr/Pi increases with Ø for all radiating environments. The value of Pt/Pi, however, decreases with increasing Ø in all cases. The maximization of Pa/Pi depends on the minimization of reflection and transmission and therefore, one can expect the maximum absorption to take place at an intermediate value of Ø. This is illustrated in Figures 4.1 and 4.2, but the absorbed power doesn't peak

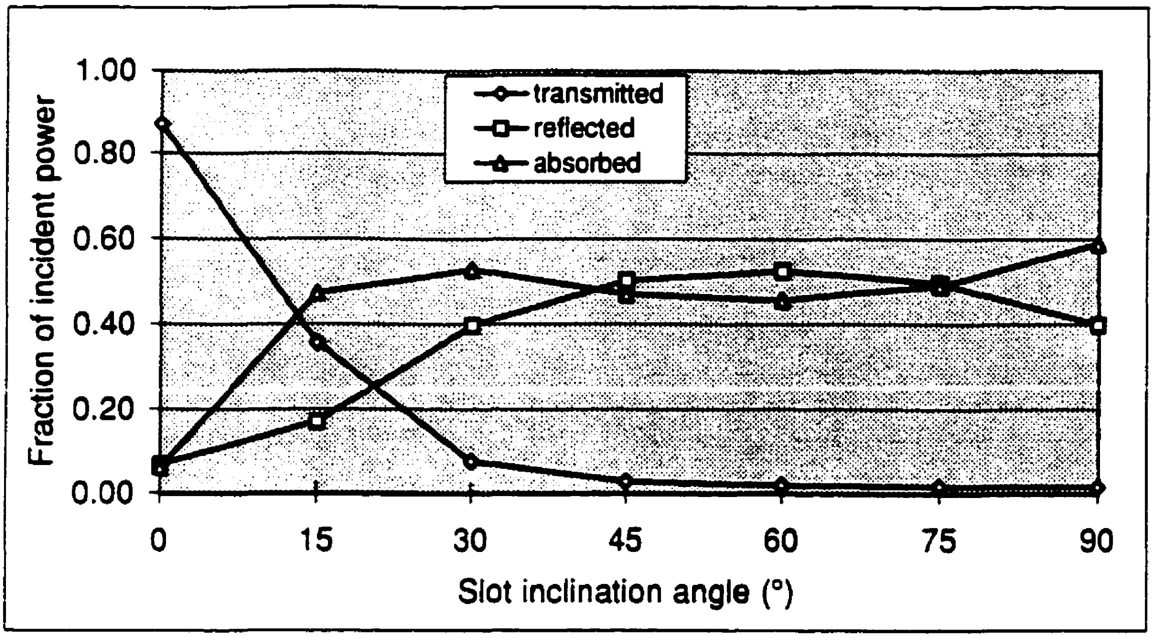

Figure 4.1 Radiation parameters for first preliminary experiment under radiation in free space conditions.

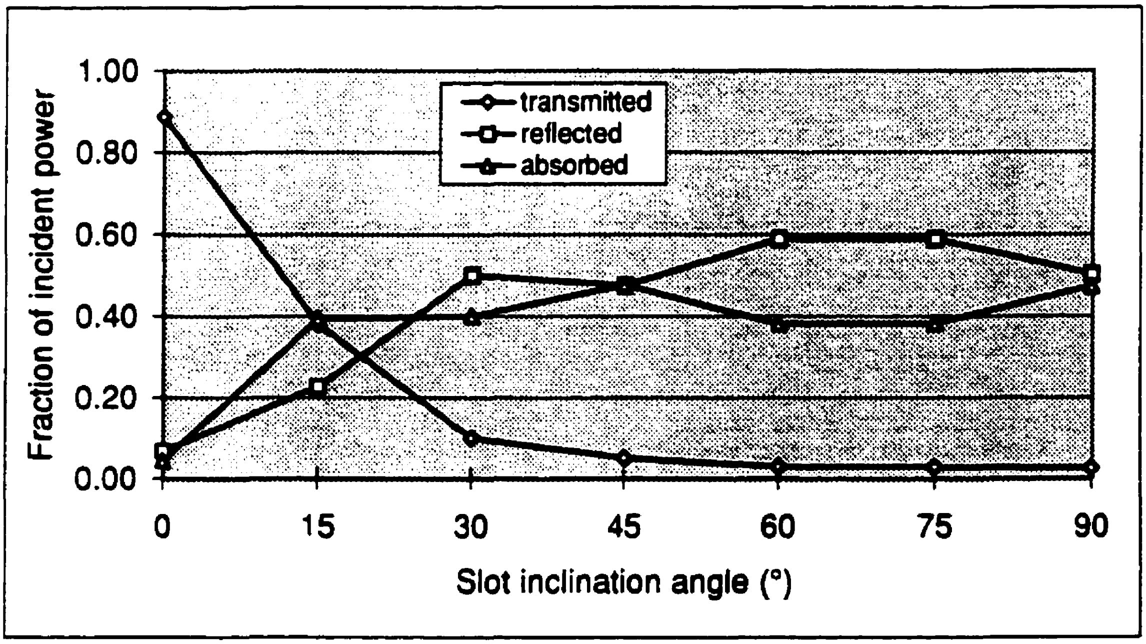

Figure 4.2 Radiation parameters for first preliminary experiment with a load at 1.5 cm above the antenna.

clearly at a specific angle. For this reason, the second preliminary experiment was conducted. However, some interesting observations can be obtained with deeper analysis of the results in Table A1.

The addition of the Teflon™ tray with respect to free space radiation had the effect of increasing transmission and reducing reflection at all values of air gap between the tray and the antenna. In fact the absorption of power was slightly increased by the addition of the tray. The addition of water above the tray resulted in reduced value of Pa/Pi. This is opposite to the expected results since water is supposed to load the antenna and couple more electromagnetic energy. The effect of the air gap clearly shows that the transmission increases with increasing air gap whereas the reflection decreases with increasing air gap. This results in the absorption increasing slightly with increasing air gap.

4.1.2 Antenna with different sets of 3 discs

The second set of experiments used only slot positions number one to three. The other nine slots were covered on the inside wall by aluminum tape and left in place at an angle of zero. All five types of slots were tested in a similar fashion. Again, ∅ was varied between 0° and 90° in steps of 15°, except for type 3, where 60°, 75° and 90° offer the same shape as 15°, 30° and 45°, but symmetrically opposite. Type 5 discs did not provide the possibility of changing ∅, in the absence of any fixed reference point on a circular shape. The other parameters examined were of the same nature as those of the first preliminary experiment except that there was no trial with the Teflon™ tray directly on top of the antenna.

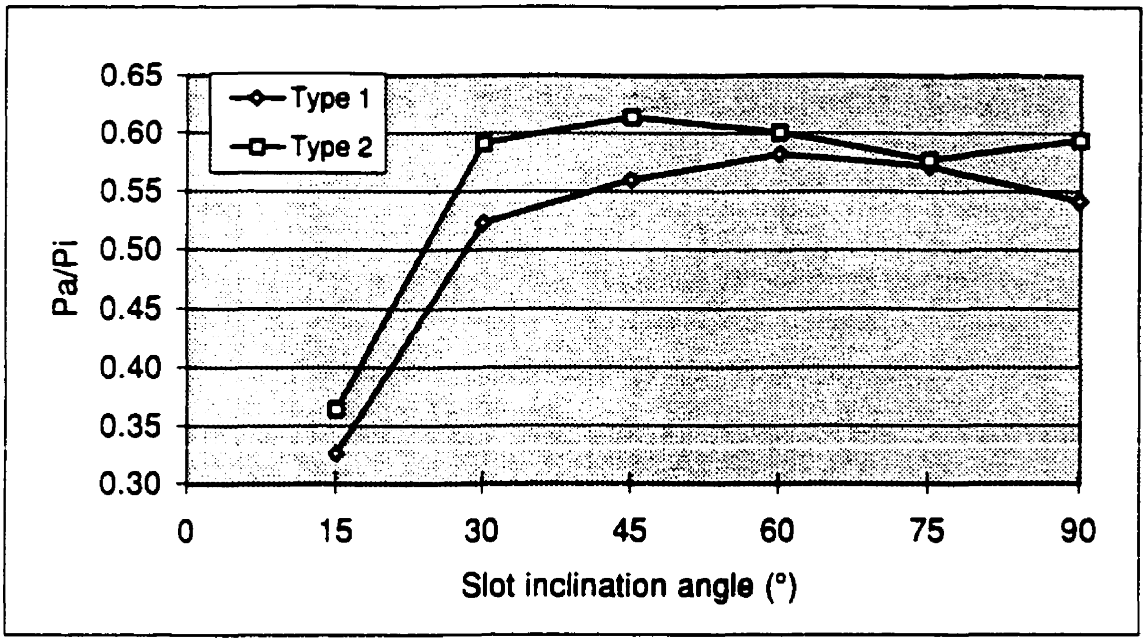

Figure 4.3 Fraction of absorbed power for second preliminary experiment under radiation in free space conditions.

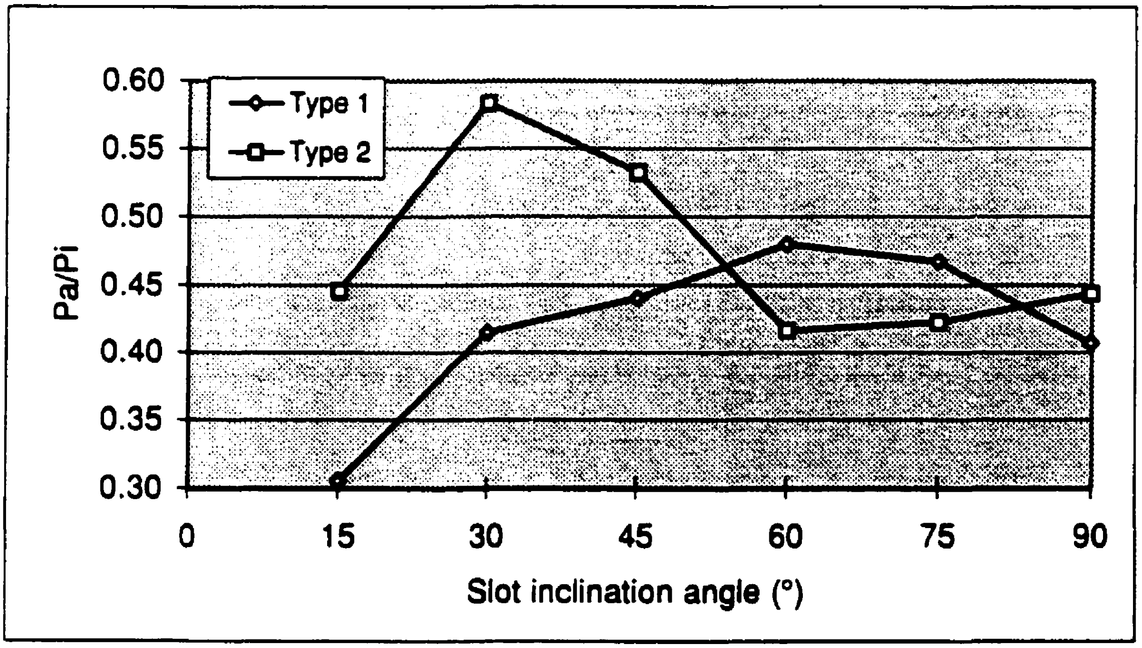

Figure 4.4 Fraction of absorbed power for second preliminary experiment with a load at 1.5 cm above the antenna.

The complete set of calculated results is listed in Table A2 of Appendix I. In general, it can be observed that Pr/Pi increases with ∅ for all radiating environments. The value of Pt/Pi, however, decreases with increasing ∅ in all cases. The maximum value of Pa/Pi is again found to take place at an intermediate value of ∅. The effect of the radiating environment is similar to those described in the previous section. However, one of the main investigation points was the effect of different slot shapes and the type 2 seems to give the best ratio of absorbed power over incident power in general. This is illustrated in Figure 4.3 for radiation in free space and in Figure 4.4 for radiation to a water load 1.5 cm above the antenna. In both cases, Pa/Pi is in general higher for the type 2 slot, but this difference decreases or disappears with increasing value of ∅. The type 4 slots gave results similar to the type 2, but are more complicated to make and the results tend to show that the additional circular holes do not change the radiation pattern much. The effect of the type 3 discs leads to similar conclusions. The type 5 slots did not show good results in any configuration of the load. Thus, for the simplicity of its design, the type 2 slot was chosen among types 2 to 5 in order to be investigated against type 1 in the corn drying simulation.

4.2 Corn drying simulation

For each experimental unit, the values of S_{11} and S_{21} were obtained from the screen of the network analyzer. These values were expressed in dB and required to be transformed into ratios of power. The following relations were used:

$$S_{11} = 10 \log\left(\frac{Pr}{Pi}\right) \tag{4.1}$$

$$S_{21} = 10\log\left(\frac{Pt}{Pi}\right) \quad (4.2)$$

Which can be tranformed to:

$$\left(\frac{Pr}{Pi}\right) = 10^{\left(\frac{S_{11}}{10}\right)} \quad (4.3)$$

$$\left(\frac{Pt}{Pi}\right) = 10^{\left(\frac{S_{21}}{10}\right)} \quad (4.4)$$

These ratios of power could then be used to obtain the ratio of absorbed power:

$$\frac{Pa}{Pi} = 1 - \left(\frac{Pr}{Pi} + \frac{Pt}{Pi}\right) \quad (4.5)$$

Equation 4.5 is based on the assumption that the measured reflection and transmission were the only two loss mechanisms involved in the experiment. Using these relations on the data obtained from the network analyzer, it was possible to average the ratios of power over the three replicates and the information is summarized in Tables 4.3 and 4.4 for both slotted discs experiment.

4.2.1 Moisture content monitoring

As mentioned previously, during the type one slot experiment, sub samples of each corn experimental unit were collected and analyzed for moisture content. This procedure was adopted in order to verify the effect of time on the corn moisture content at room temperature. For a given replicate

Table 4.3: Radiation parameters for corn drying simulation experiment at mid-sweep frequency of 2.45 GHz for type 1 slotted discs. Average of three replicates.

% M.C. (w.b.)	Angle (°)	Reflection Pr/Pi	Transmission Pt/Pi	Absorption Pa/Pi
14	25	0.27	0.20	0.53
14	35	0.41	0.11	0.47
14	45	0.47	0.07	0.46
14	55	0.50	0.05	0.45
14	65	0.51	0.04	0.44
14	75	0.41	0.04	0.55
22	25	0.37	0.12	0.51
22	35	0.49	0.05	0.46
22	45	0.52	0.03	0.45
22	55	0.56	0.02	0.42
22	65	0.54	0.02	0.44
22	75	0.52	0.01	0.47
30	25	0.40	0.10	0.51
30	35	0.39	0.04	0.56
30	45	0.46	0.03	0.50
30	55	0.47	0.04	0.49
30	65	0.41	0.03	0.56
30	75	0.43	0.04	0.53

Table 4.4: Radiation parameters for corn drying simulation experiment at mid-sweep frequency of 2.45 GHz for type 2 slotted discs. Average of three replicates.

% M.C. (w.b.)	Angle (°)	Reflection Pr/Pi	Transmission Pt/Pi	Absorption Pa/Pi
14	25	0.23	0.02	0.75
14	35	0.40	0.01	0.59
14	45	0.38	0.00	0.61
14	55	0.19	0.00	0.81
14	65	0.27	0.00	0.73
14	75	0.31	0.00	0.69
22	25	0.22	0.01	0.77
22	35	0.37	0.00	0.63
22	45	0.37	0.00	0.63
22	55	0.19	0.00	0.81
22	65	0.28	0.00	0.71
22	75	0.30	0.00	0.70
30	25	0.15	0.01	0.84
30	35	0.26	0.01	0.73
30	45	0.30	0.01	0.69
30	55	0.14	0.01	0.86
30	65	0.22	0.01	0.77
30	75	0.22	0.01	0.77

run, the time of each measurement was noted down and a graph of moisture profile versus relative experiment time can be plotted for each set of moisture content. The analysis of all moisture content profiles revealed that the corn is not drying during the time the experiment takes place. The moisture vs time profile for the first replicate of the 32% M.C. is displayed in Figure 4.5.

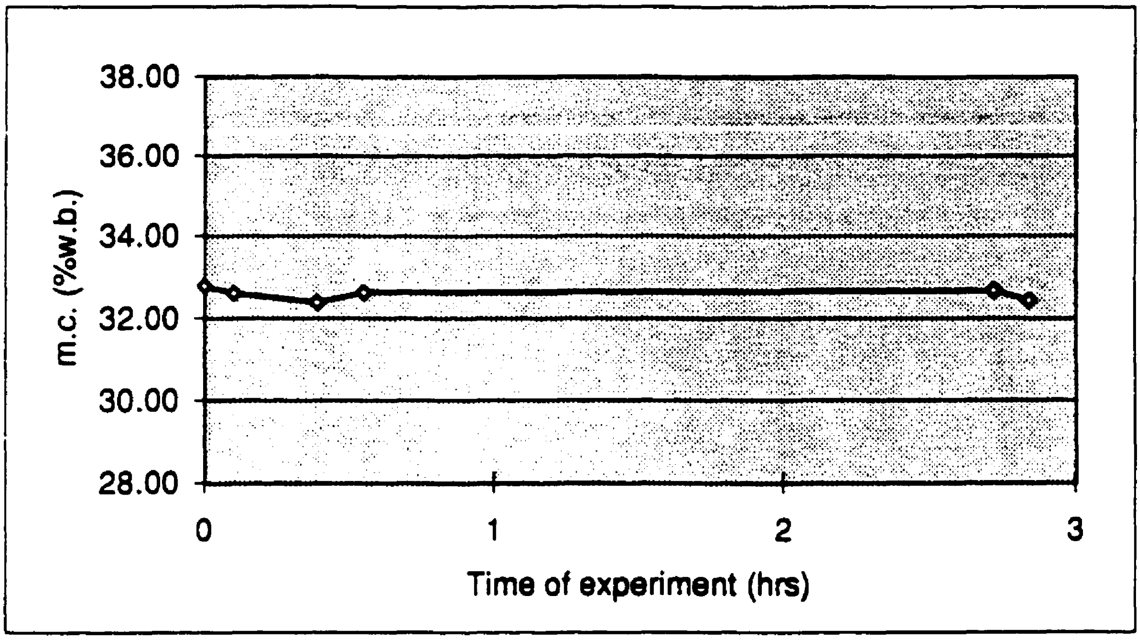

Figure 4.5 Moisture profile vs time for 32 % m.c. corn of the first replicate.

4.2.2 Slot width effect

In general, the type 2 slotted discs showed a better coupling of the incident power to the load. This is illustrated for the 32 % m.c. corn in Figure 4.6 where Pa/Pi is varying between 70% and 85% for the type 2 slots whereas it is varying between 50% and 60% for the type 1 slots. The reflection seems to be responsible for most of this effect as illustrated in Figure 4.7 where Pr/Pi for type 1 is around 20% higher than for type 2 slots. The transmission is also higher for type 1 slots, but in a less important fashion as seen in Figure 4.8.

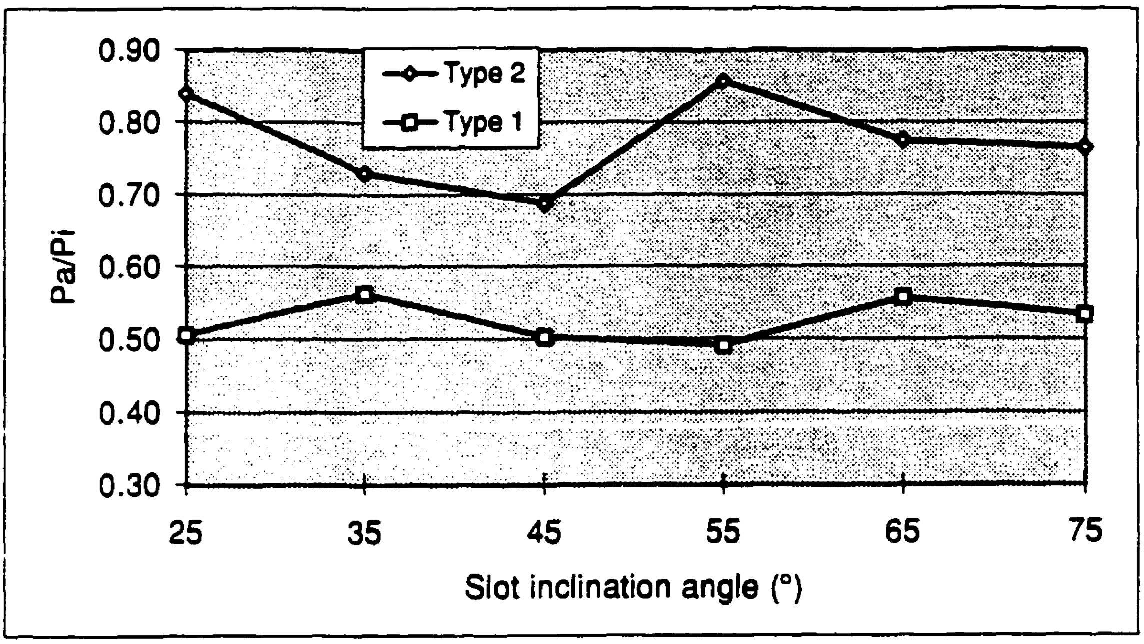

Figure 4.6 **Fraction of absorbed power vs Ø in corn drying simulation experiment with 32 % m.c. corn for type 1 and 2 slotted discs.**

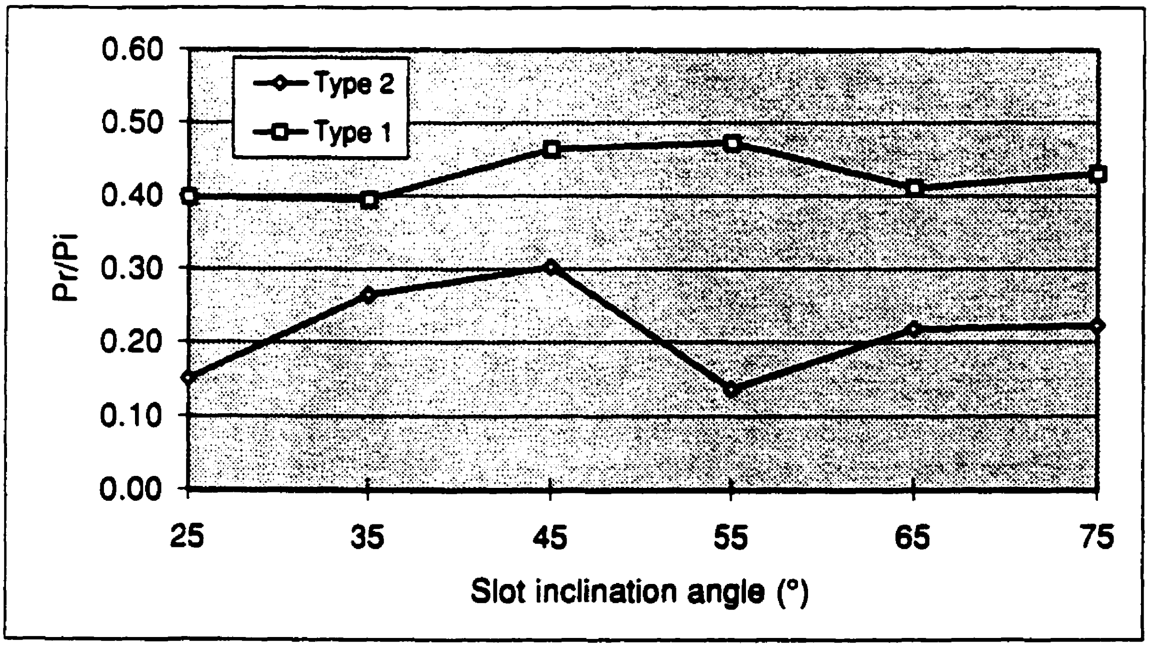

Figure 4.7 **Fraction of reflected power vs Ø in corn drying simulation experiment with 32 % m.c. corn for type 1 and 2 slotted discs.**

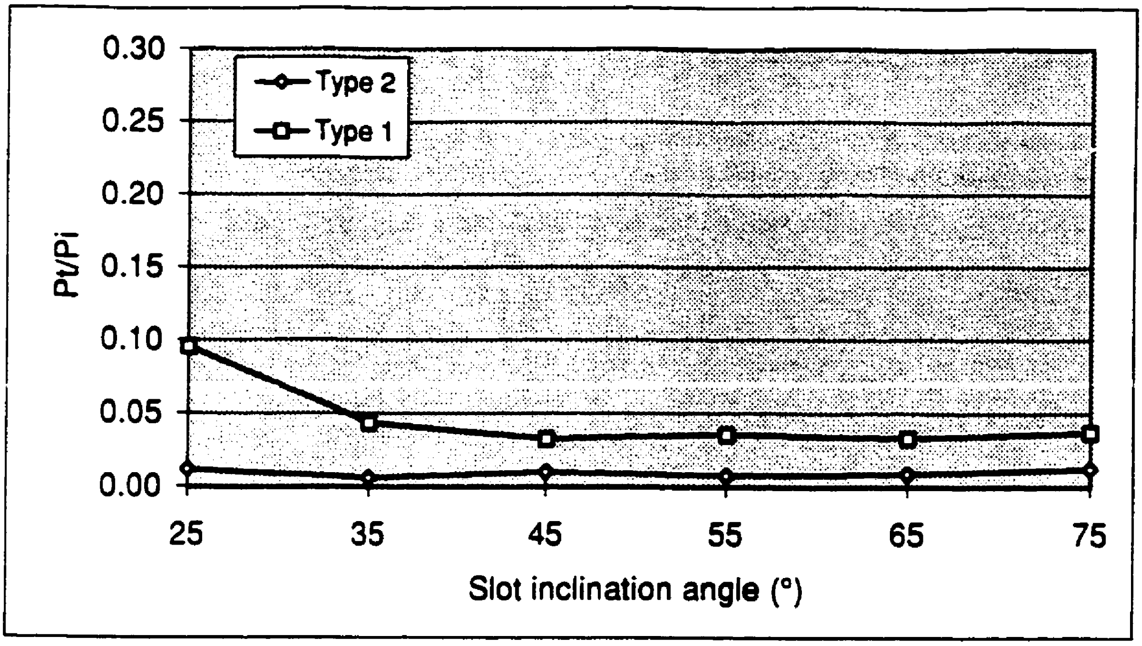

Figure 4.8 Fraction of transmitted power vs Ø in corn drying simulation experiment with 32 % m.c. corn for type 1 and 2 slotted discs.

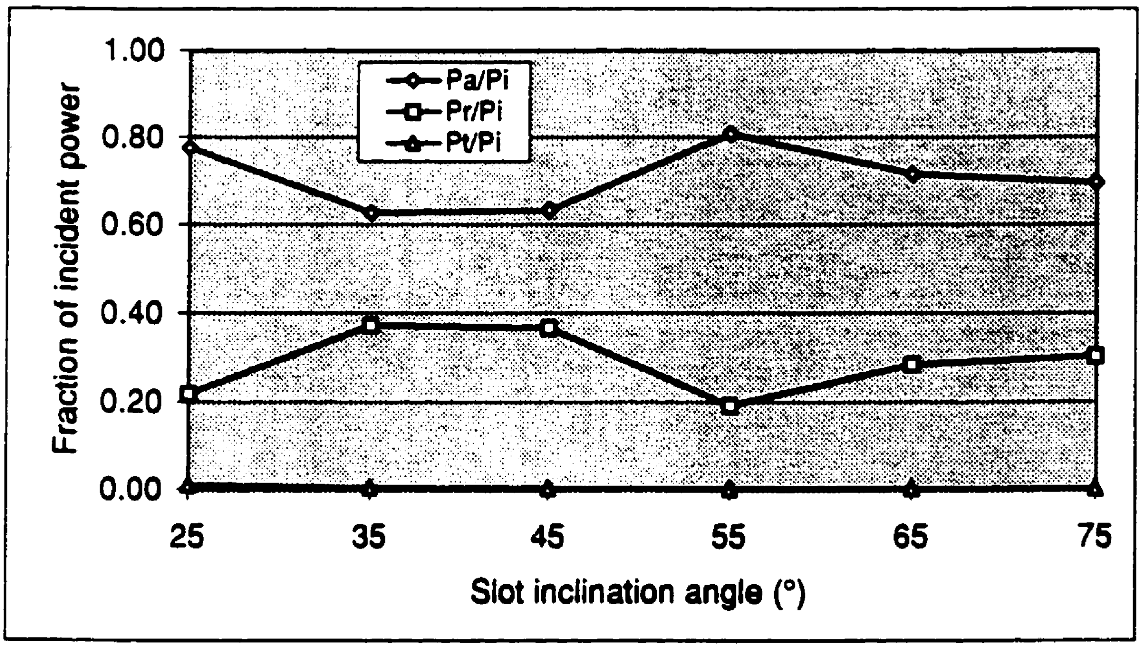

Figure 4.9 Radiation characteristics of the antenna vs Ø with type 2 slotted discs and 24 % m.c. corn.

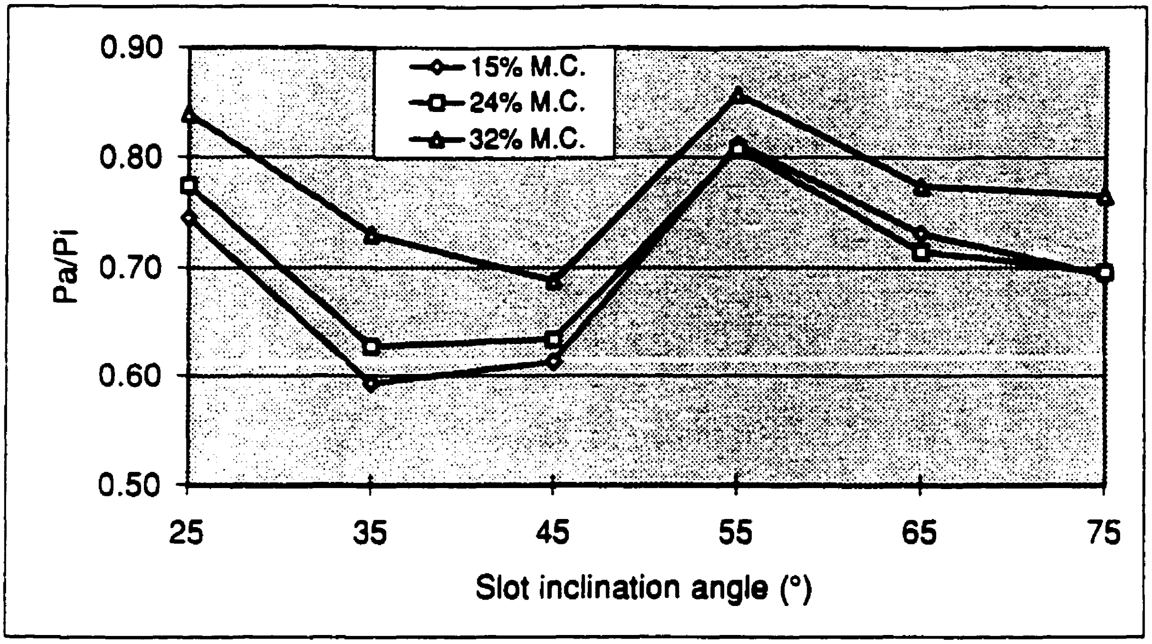

Figure 4.10 Fraction of absorbed power vs Ø for type 2 slotted discs and various corn m.c.

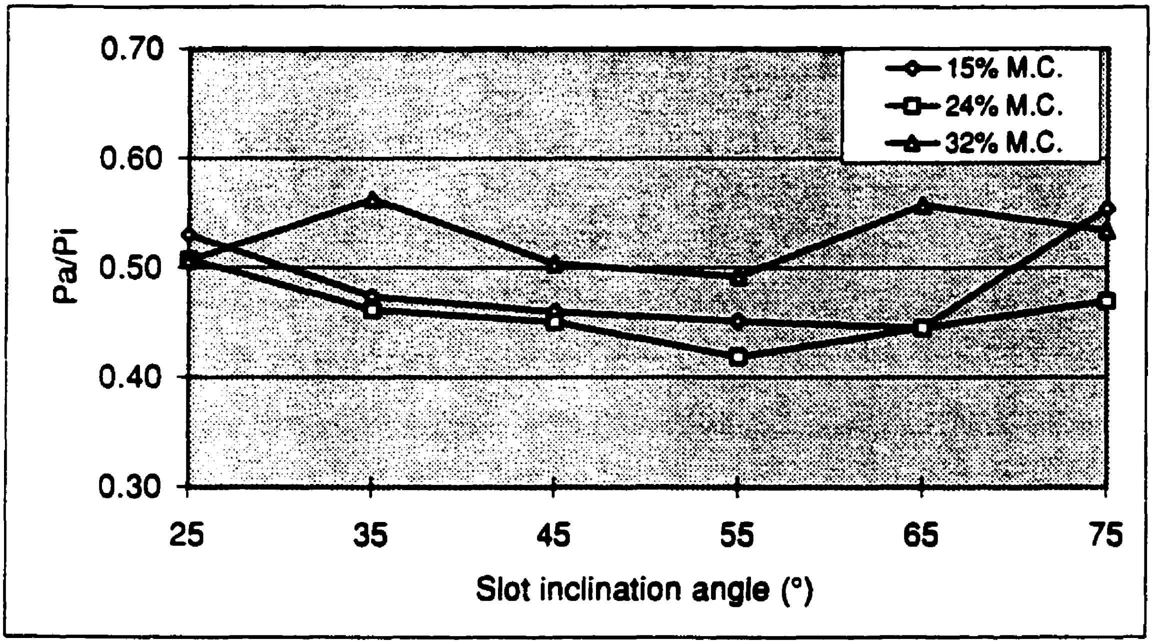

Figure 4.11 Fraction of absorbed power vs Ø for type 1 slotted discs and various corn m.c.

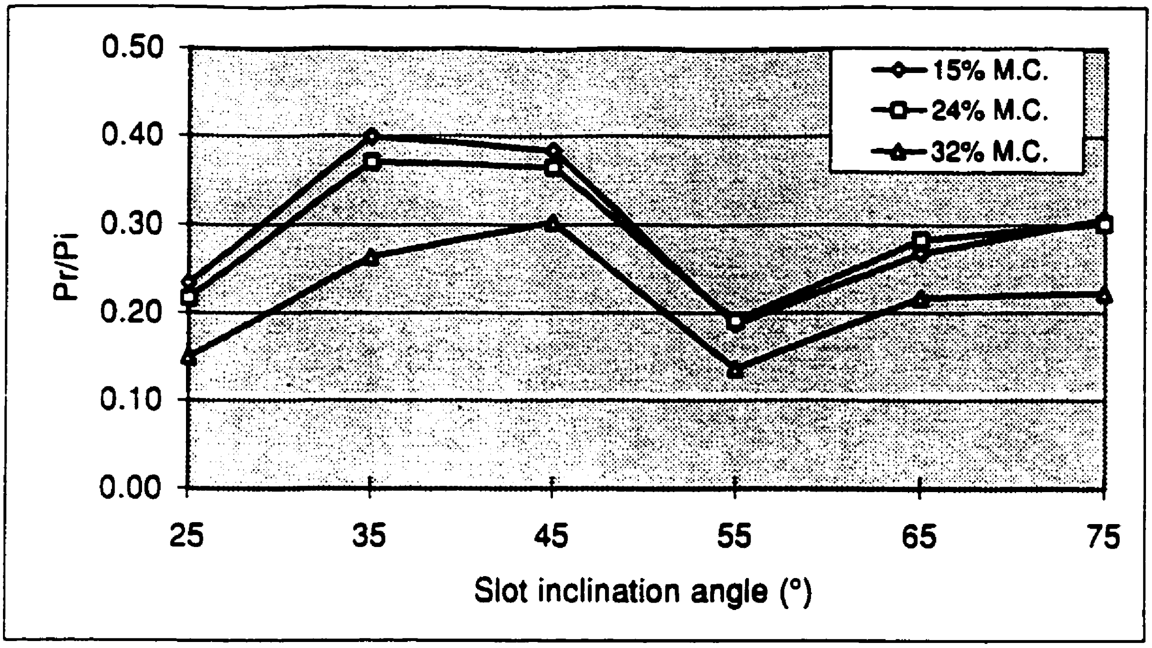

Figure 4.12 Fraction of reflected power vs Ø for type 2 slotted discs and various corn m.c.

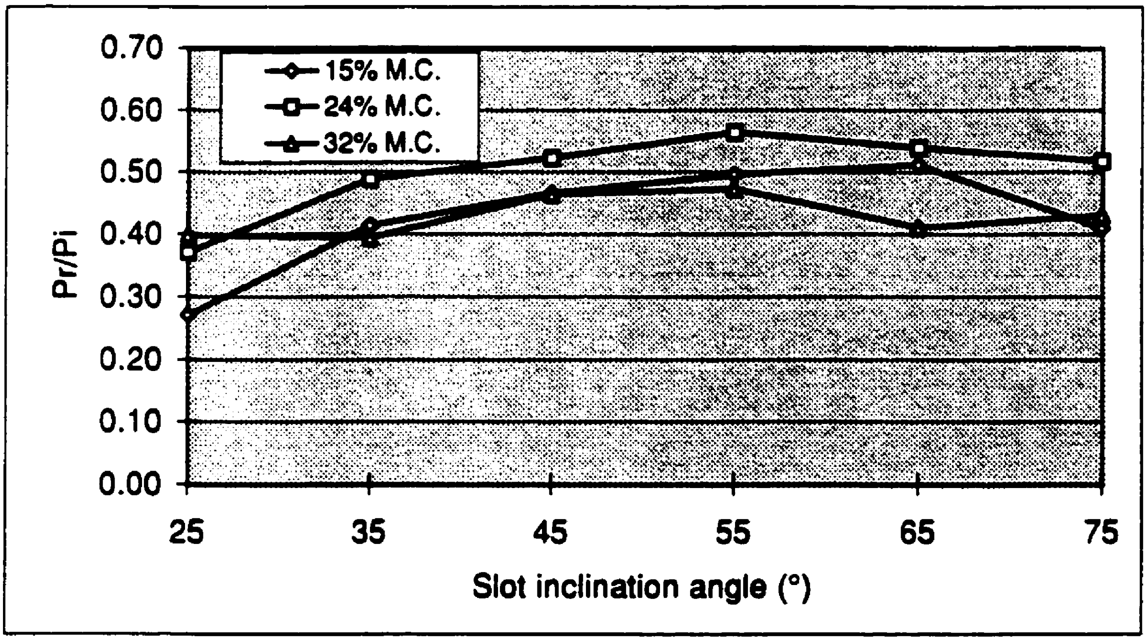

Figure 4.13 Fraction of reflected power vs Ø for type 1 slotted discs and various corn m.c.

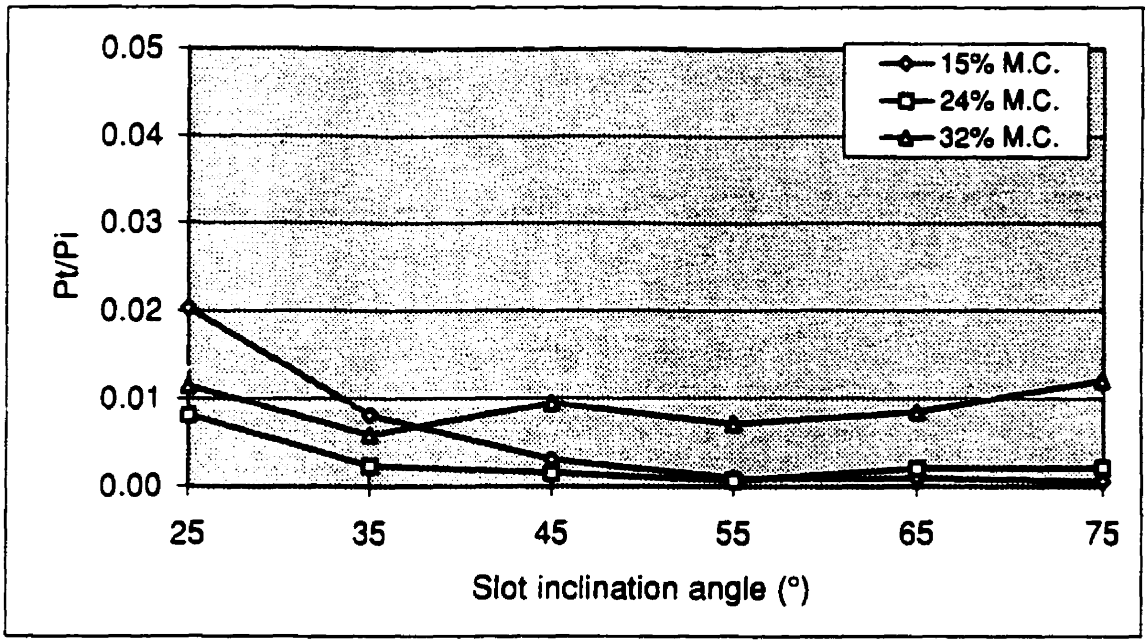

Figure 4.14 Fraction of transmitted power vs Ø for type 2 slotted discs and various corn m.c.

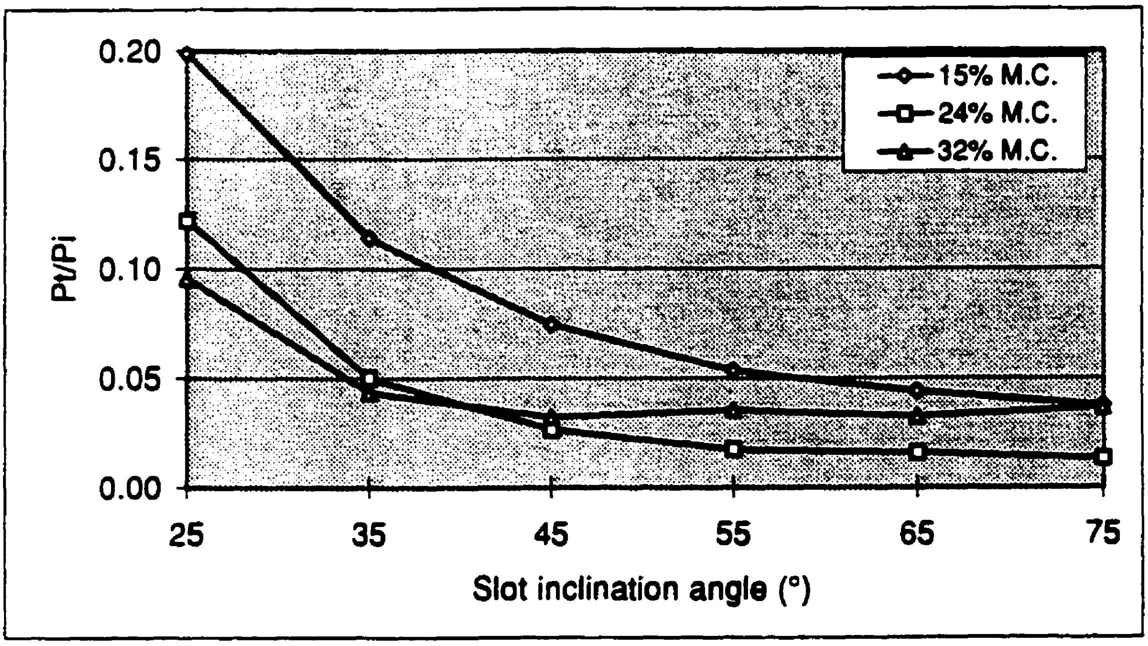

Figure 4.15 Fraction of transmitted power vs Ø for type 1 slotted discs and various corn m.c.

The reflection accounts for most of the power losses and this is especially true for the type 2 slots. Figure 4.9 depicts this fact by showing all fractions of incident power for the type 2 slots with the 24% M.C. corn. This observation is also true at other moisture contents.

4.2.3 Moisture content and slot inclination angle effects

The effects of moisture content and slot inclination angle ∅ on the radiating characteristics of corn for type 1 and 2 slotted discs are illustrated in Figures 4.10 to 4.15. For both type of slots, the higher moisture corn seems to have contributed more to the absorption of the incident power. The decrease in reflection with increasing moisture content seems to be the driving factor for the increase in absorption. The effect is not so clear for transmission.

The effect of ∅ can be observed for the type 2 slots where Pa/Pi peaks at 55° and Pr/Pi has its lowest value. The effect on Pt/Pi is again not clear. For the type 1 slots, the effect of ∅ is not obvious, except for transmission, which decreases regularly with increasing angle.

V SUMMARY AND CONCLUSIONS

A study of the radiating characteristics of a slotted waveguide antenna mounted in a setup that simulates the coupling to a grain conveying tube was carried out. The effect of the slot inclination angle Ø and the shape of the slots as well as the grain moisture contents of corn were the main points of investigation.

A special waveguide antenna, which can allow modifications of its design parameters without having to rebuild it for each combination was constructed during the experiment. The antenna falls in the category of a slotted waveguide with series slots cut on the broad side and constitutes a popular means of coupling electromagnetic energy to a material for the purpose of heating or drying.

As explained in literature, it was observed that in general, the reflection of the microwaves is increasing with increased slot inclination angle Ø and the transmission is decreasing with increasing value of Ø. This results in the optimum value of the absorption of the microwaves being observed at a median value of the slot inclination angle. The results obtained tend to point out 55° as an optimum slot angle for slots having a width of 13 mm. Slots with a width of 6 mm did not show a regular behaviour and the effect of Ø was not clearly identified. Overall, the wider slots presented much lower reflection and transmission characteristics.

However, the wide slots used in the experiment were not machined as precisely as the narrow slots and therefore, a better fabrication method involving the direct machining of the slots on the walls of the waveguide should improve the results in terms of energy coupling to the load. The tip of the screws used to maintain a good surface contact between the discs and the wall of the waveguide may also have protruded inside the guide and caused some extra reflection. The thickness of the material used for the narrow slots may have been a mitigating factor on their radiating characteristics. The effect of the wall thickness was neglected in the present study.

The measurements carried out during the experiments were achieved at very low values of power and may differ from those that would be observed in an actual heating and drying application. The operation of the antenna in such an environment would probably require the use of a short circuit at one end of the waveguide and thus result in a standing wave pattern. The reflection might be better controlled by such dispositions.

The 57.7 mm length of the slots used in the experiments was inspired by values suggested in literature for industrial microwave applications (Bialod and Marchand, 1986). However, this value is slightly different from the value of a half free space wavelength (61.1 mm) often suggested in theory.

VI RECOMMENDATIONS

The present work constitutes a first attempt at studying the radiating characteristics of a slotted waveguide antenna for the pupose of grain drying. In order to come up with a complete microwave continuous flow dryer, several actions should be undertaken:

- The complete theoretical study of the microwave aspect of the antenna should be derived in order to validate the experimental conclusions.
- A larger value of the slot length should be investigated
- Similar studies could involve research with other grains than corn
- The system should be tested at high power application as long as wave leakage prevention mechansisms are utilized.
- The use of hot air as the moisture carrier medium can be considered
- An eventual dryer could be configured in an octagonal shape with multiple waveguides perpendicular to each other as shown in Figure 3.6.

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APPENDICES

Table A1: Fractions of incident power for preliminary test with 12 aluminum type 1 discs.

Slot Angle	radiation in free space			air gap = 1.5 cm teflon alone			air gap = 1.5 cm water load			air gap = 0.5 cm teflon alone			air gap = 0.5 cm water load			without air gap teflon alone			without air gap water load		
(°)	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi
0	0.871	0.068	0.061	0.881	**0.068**	0.051	0.887	**0.068**	0.044	0.910	**0.072**	0.018	0.904	**0.072**	0.024	0.853	0.072	0.074	0.845	0.072	0.082
15	0.356	**0.170**	0.474	0.406	0.143	0.451	0.379	0.226	0.394	0.470	0.076	0.454	0.525	0.127	0.348	0.622	**0.025**	0.352	0.605	**0.064**	0.331
30	0.075	0.397	0.528	0.112	0.354	0.534	0.100	0.500	0.400	0.152	0.281	0.566	0.186	0.334	0.480	0.268	0.177	0.555	0.270	0.199	0.531
45	0.028	0.502	0.470	0.048	0.474	0.477	0.050	0.474	**0.476**	0.071	0.423	0.506	0.089	0.474	0.437	0.144	0.282	**0.574**	0.147	0.252	**0.601**
60	0.019	0.525	0.456	0.033	0.442	0.526	0.030	0.589	0.381	0.041	0.394	0.566	0.056	0.468	0.476	0.094	0.351	0.555	0.095	0.331	0.574
75	0.015	0.495	0.490	0.029	0.468	0.503	0.029	0.589	0.383	0.034	0.372	**0.594**	0.046	0.442	**0.513**	0.079	0.372	0.550	0.069	0.442	0.490
90	**0.013**	0.398	**0.588**	**0.027**	0.376	**0.597**	**0.025**	0.501	0.473	**0.032**	0.447	0.521	**0.044**	0.531	0.425	**0.078**	0.376	0.546	**0.062**	0.447	0.492

Table A2: Fractions of incident power for preliminary test with 3 discs of various shapes.

Slot angle (°)	radiation in free space			Air gap = 1,5 cm teflon alone			Air gap = 1,5 cm water load			Air gap = 0,8 cm teflon alone			Air gap = 0,8 cm water load		
slot angle (°)	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi	Pt/Pi	Pr/Pi	Pa/Pi
15	0.627	**0.048**	0.326	0.675	**0.048**	0.278	0.619	**0.075**	0.305	0.714	**0.030**	0.256	0.695	**0.063**	0.242
30	0.350	0.127	0.523	0.425	0.101	0.474	0.359	0.226	0.415	0.453	0.057	0.490	0.442	0.143	0.416
45	0.214	0.226	0.560	0.278	0.160	0.562	0.240	0.320	0.440	0.302	0.120	0.578	0.318	0.240	**0.442**
60	0.164	0.254	**0.582**	0.220	0.202	0.578	0.200	0.320	**0.480**	0.239	0.170	0.591	0.258	0.320	0.422
75	**0.147**	0.282	0.571	**0.200**	0.211	**0.589**	**0.178**	0.355	0.467	**0.216**	0.188	**0.595**	**0.245**	0.316	0.438
90	0.153	0.305	0.541	0.205	0.243	0.552	0.186	0.407	0.406	0.221	0.204	0.575	0.268	0.324	0.408
Type 2 discs															
0	0.820	0.108	0.071	0.824	0.108	0.067	0.828	0.108	0.064	0.822	0.108	0.069	0.836	**0.102**	0.062
15	0.590	**0.046**	0.364	0.617	**0.065**	0.319	0.473	**0.081**	0.446	0.681	0.058	0.262	0.562	**0.102**	0.335
30	0.316	0.092	0.591	0.372	0.087	0.540	0.209	0.207	**0.584**	0.470	**0.052**	0.478	0.296	0.185	**0.519**
45	0.184	0.202	**0.614**	0.255	0.161	**0.585**	0.108	0.360	0.532	0.312	0.114	0.574	0.177	0.321	0.502
60	0.145	0.255	0.601	0.195	0.227	0.578	0.076	0.508	0.416	0.255	0.161	0.585	0.171	0.381	0.448
75	0.124	0.299	0.577	0.168	0.252	0.580	0.076	0.502	0.422	0.209	0.200	0.591	0.136	0.448	0.416
90	**0.116**	0.290	0.594	**0.160**	0.258	0.582	**0.070**	0.486	0.444	**0.199**	0.194	**0.607**	**0.135**	0.459	0.406
Type 3 discs															
0	0.113	**0.325**	**0.562**	0.169	**0.274**	0.558	0.150	0.515	0.335	0.179	**0.230**	0.590	0.226	0.434	0.341
15	0.101	0.367	0.532	0.150	0.292	0.559	0.114	**0.462**	**0.423**	0.173	0.245	0.582	0.206	0.412	0.382
30	0.079	0.366	0.554	0.129	0.308	0.562	**0.106**	0.489	0.405	0.149	0.259	0.591	**0.147**	**0.259**	**0.594**
45	**0.076**	0.386	0.538	**0.125**	0.307	**0.568**	0.095	0.486	0.419	**0.142**	0.258	**0.600**	0.150	0.409	0.441
Type 4 discs															
0	0.760	**0.129**	0.110	0.759	0.129	0.112	0.764	**0.129**	0.107	0.762	0.129	0.109	0.762	**0.129**	0.109
15	0.560	0.137	0.303	0.578	**0.097**	0.325	0.445	**0.129**	0.426	0.638	0.154	0.208	0.541	0.137	0.322
30	0.283	**0.129**	0.587	0.348	0.122	0.530	0.199	0.258	**0.543**	0.429	**0.069**	0.503	0.293	0.217	**0.490**
45	0.174	0.205	**0.621**	0.244	0.163	0.593	0.126	0.365	0.510	0.308	0.103	0.589	0.196	0.325	0.479
60	0.124	0.256	0.619	0.189	0.204	**0.607**	**0.083**	0.431	0.487	0.233	0.153	**0.614**	**0.141**	0.406	0.453
75	**0.110**	0.288	0.602	**0.173**	0.229	0.598	0.088	0.483	0.429	0.208	0.182	0.610	0.142	0.406	0.452
90	0.114	0.320	0.567	0.177	0.240	0.584	0.094	0.507	0.399	**0.202**	0.191	0.608	**0.141**	0.380	0.479
Type 5 discs															
no slot	0.612	0.285	0.103	0.624	0.269	0.107	0.653	0.285	0.062	0.569	0.269	0.162	0.640	0.269	0.091