University of Cincinnati

Date: 8/8/2014

I, Sai Munesh Bejjavarapu , hereby submit this original work as part of the requirements for the degree of Master of Science in Aerospace Engineering.

It is entitled:

An experimental model for guided microwave backscattering from wet insulation in pipelines

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**An experimental model for guided microwave backscattering from wet
insulation in pipelines**

A thesis submitted to the

Division of Research and Advanced Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Master of Science (M.S.)

in the Department of Aerospace Engineering and Engineering Mechanics
of the College of Engineering and Applied Science
of the University of Cincinnati

2014

by

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B. Tech. Aerospace Engineering, Indian Institute of Technology Madras, 2012

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Abstract

Corrosion under insulation (CUI) is a common cause of pipeline failure in the oil and gas industry. Its detection with conventional inspection techniques is challenging due to the presence of the insulation layer and a protective metallic cladding that prevent direct access to the pipe surface. Currently, several techniques are being developed to detect sections of wet insulation since water is a necessary precursor to corrosion. Among these, guided microwave testing (GMT) has been proposed as a cost-effective approach to screen an extended length of pipeline. The sensitivity of GMT is dependent on the strength of microwave reflections from wet volumes of insulation and has been demonstrated in the case of relatively abrupt transitions from dry to fully saturated insulation. This thesis investigates the performance of GMT in the presence of saturation gradients characterizing more gradual transitions. Due to the lack of detailed field observations about realistic saturation paths, the thesis proposes model experiments of saturation dynamics in a highly permeable material in a first attempt to determine saturation profiles resulting from capillary rise and seepage. The experimental observations reveal that the extent of the transition region is typically much smaller than the wavelength of the probing microwave signal and therefore has a limited effect on the amplitude of the reflected signal.

Acknowledgements

I would like to offer my sincerest gratitude to my thesis advisor, Professor Francesco Simonetti for his guidance, patience and support throughout my research endeavors at the University of Cincinnati. I am so grateful for him, and have learned so much from his experience. I am also grateful for my thesis committee members, Professor Peter B. Nagy and Professor Gui-Rong Liu.

I would also like to thank Curtis Fox for all his assistance with obtaining equipment for experimentation and his insights into all computer hardware and software problems.

I would like to thank my fellow graduate students, Carson Wiley and Rodrigo for all their assistance in debugging MATLAB scripts and other software and their help in solving problems arising during research.

I would also like to thank my friends, Dhaval Shiyani, Amey Godambe, Shrirang Deshpande and Arun Gopal Rajagopalan for their support and encouragement while pursuing this degree.

Finally I would like to address my sincerest gratitude to my parents in India, my father Nageswara Rao Bejjavarapu and my mother, Sri Kala Bejjavarapu for their never ending support and kind words throughout my graduate and undergraduate career which have helped me overcome major challenges while pursuing this degree. Also I would like to thank all my friends in India and the States.

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Chapter I

1. INTRODUCTION

When pipelines are fitted with thermal insulation to maintain the temperature of the liquid they carry above ambient conditions, corrosion initiating on the outer surface of the pipe may go undetected and lead to catastrophic failure. Corrosion under insulation (CUI) forms when the outer metallic cladding used to protect the insulation deteriorates over time resulting in a path for water ingress. Once water enters the insulation, the wet area provides a means for corrosion to initiate and progress at a fast rate due to the high working temperature of the pipe. CUI therefore represents a major challenge in the oil and gas industry and has been responsible for a number of accidents that have resulted in prolonged production outage and substantial environmental pollution.

Detection of CUI is challenging since there is no direct access to the pipe and removal of the outer cladding and insulation can be prohibitively expensive. Therefore, numerous conventional and non-conventional inspection methods have been investigated with various degree of success. However, reliability and cost of the inspection remain major issues and an industry standard for CUI detection is yet to emerge [2].

There are two main strategies that have been proposed for the detection of CUI which are dependent on whether the target of the inspection are the actual corrosion defects in the pipe or water volumes inside the insulation layer; the rationale for detecting water being that it is a necessary precursor to CUI. Important methods that fall in the first category are profile radiography [3] and pulsed eddy currents (PEC) [4]. Radiography suffers from a slow rate of coverage and radiation risks for inspectors severely restrict its applicability [5]. Slow rate of coverage is also an issue with PEC whose major limitation is however sensitivity

to the electromagnetic and geometrical properties of the metallic cladding that can have a dominant effect on the measured signals. An alternative to the previous methods could be long range guided ultrasonic wave screening [6, 7] which is routinely used for the detection of corrosion defects in pipes. However, it requires the removal of a section of insulation to clamp an array of transducers around the pipe circumference which is time consuming and could indeed produce a site for water ingress once the array is removed and the insulation restored.

The possibility of detecting water inside the insulation has also been investigated with a number of techniques ranging from infrared thermography and neutron backscattering [8] to the use of optical fibers embedded in the insulation to monitor humidity [9] or even less sophisticated approaches that use external containers placed at each insulation joint to collect water that has previously penetrated through cladding [10]. As in the case of direct detection of corrosion damage, these techniques are not suited to inspect the full volume of an insulated pipeline either due to cost or inherently limited coverage.

This thesis instead focuses on a recent guided microwave method that has been introduced to screen an extended length of pipeline for the presence of wet insulation from a single sensor position [11, 12]. Here, the pipe and metallic cladding naturally form a large coaxial transmission line in which the insulation acts as a dielectric and supports the propagation of microwave signals. The microwave regime of the electromagnetic spectrum is chosen because the insulation is almost transparent to microwave radiation at these frequencies thus resulting in low attenuation and hence long-range inspection capabilities. The inspection is performed by launching a microwave signal from an array of antennas permanently installed at one location along the pipeline. The antennas are inexpensive metallic rods inserted inside the insulation through small holes in the cladding which are subsequently sealed.

Wet insulation is detected according to the radar principle; water results in the partial reflection of the incident microwave signal owing to the permittivity contrast between dry and wet insulation. By timing the journey of the reflected microwave signal the position of the water volume can be determined accurately.

Laboratory experiments conducted on a 6" diameter pipe with 3" thickness insulation have shown that water volumes equivalent to 5% of the insulation annulus cross-sectional area are readily detectable [11]. Importantly, the microwave signal can travel through bends and supports with limited attenuation [12] thus opening the possibility for monitoring complex pipeworks such as those present in refineries and other petrochemical plants.

The sensitivity of the microwave approach is dependent on the strength of the signal reflected by the wet insulation relative to the background noise - the amplitude of the reflected signal must be greater than the noise floor. The noise level can be reduced by a careful design of the antenna array whose primary function is to suppress unwanted guided modes as discussed in Ref. [11]. On the other hand, the amplitude of the reflected signals is dependent on the characteristics of the wet insulation volume. Assuming that the insulation acts as a porous medium the spatial distribution of the water saturation fraction becomes the driving factor determining the strength of the reflection. In particular, it can be expected that an abrupt interface between dry and 100% water saturated insulation will result in a larger reflection than that produced by a continuous saturation gradient between the dry and completely saturated regions.

The initial studies presented in Ref. [11] have investigated microwave reflection from water volumes in plastic containers inserted in the insulation layer that therefore formed abrupt interfaces. The aim of this thesis is to expand the scope of the work in Ref. [11] to consider the effect of saturation gradients. A range of insulation materials including rockwool, and

polyurethane foam are commonly used in industrial applications; however, limited data is available as to what constitutes realistic saturation distributions and gradients within these materials. Moreover, depending on the location in which water breaches the cladding different mechanisms can drive water absorption including seepage and capillary rise which may in turn lead to different saturation gradients. A further complication arises from the variability of the hydraulic properties of the insulation with time; for instance rockwool material is known to lose its hydrophobic properties with exposure to field conditions. As a result, the current understanding of water saturation inside the insulation is very limited and not sufficient to address the problem of microwave reflectivity. In this paper we therefore propose a study which is a first attempt to simulate the characteristics of water saturation in the insulation by means of a set of model experiments with a highly permeable and porous material.

After highlighting some of the key aspects of water absorption in porous media in Ch. 2 the background of microwave excitation and propagation in coaxial waveguides is provided in Ch. 3. A simple one-dimensional model is provided in Ch. 4 to study microwave reflection from an idealized saturation gradient. The experimental set up described in Ch. 5 is then used to perform the microwave reflection measurements reported in Ch. 6 for different water saturation cases and absorption mechanisms. Concluding remarks are given in Ch. 7.

Chapter II

2. MECHANISMS OF WATER ABSORPTION

While the problem of diffusion and transport of a substance in a saturated porous medium has been the subject of extensive research fewer studies have addressed the propagation of saturation fronts in dry porous media.

Uptake of water in a porous medium is typically ascribed to a capillary rise phenomenon and is described by adapting the classical Washburn equation [13] for cylindrical capillary tubes to the case of a porous cylinder as shown in Fig. 2.1(a). The model is used to predict the velocity at which the saturation front rises and leads to an expression for the position of the front, z_F , as function of time, t , according to [1]

$$t = \theta_s \left(\frac{h_e + z_R}{K_s} \right) \ln \left(\frac{z_R + h_e}{z_R + h_e - z_F} \right) - \frac{\theta_s z_F}{K_s}, \quad (2.1)$$

where z_R is the positive pressure head imposed at $z = 0$, θ_s is the porosity (ratio between the total pore volume and bulk volume of the material), K_s is the saturated hydraulic conductivity that describes the ease at which fluid can move through saturated porous media and depends on the permeability of the material, density, and viscosity of the fluid. The constant h_e is the equilibrium height for a non-porous capillary tube with the same cumulative mass absorbed [1].

The Washburn model assumes a discontinuous wet-dry transition interface and it predicts that after a relatively short time the front tends to an equilibrium height (the saturation front stops advancing) as shown by the dashed curve in the diagram of Fig.2.1(b). Hackett [14]

FIG. 2.1: Capillary water rise in a porous medium. (a) Diagram of a typical capillary rise experiment showing the geometrical parameters used in the Washburn equation - the diagram is adapted from [1]; (b) Position of the saturation front as a function of time as predicted by the Washburn model for an abrupt wet-dry transition (dashed curve) and with a saturation gradient (solid curve).

showed that in sand the Washburn equation correctly describes the early stages of the water ascent however he also noticed that the water rise could continue beyond the equilibrium time predicted by the Washburn model [see solid curve in Fig.2.1(b)]. More recently Delker et al. [15] studied the rise of water in a column of glass beads and observed that the water level continued to climb beyond the Washburn equilibrium height with no sign of reaching equilibrium. Similar experiments have led to the same observations by Lago and Araujo [16] who also noted that at the time when the water rise starts to deviate from the Washburn model a loss in definition of the saturation front occurs leading to a saturation gradient over a transition region as shown in Fig. 2.1(a). The extent of the transition becomes significant for times past the equilibrium point predicted by the Washburn model while it is negligible during the early times. Lockington and Parlange [1] have shown that the long term behavior of the saturation front can be correctly predicted by considering the saturation gradient in

the Washburn model.

Current studies have been limited to one-dimensional absorption problems whereas water uptake in the pipe insulation is a fully three-dimensional phenomenon. Moreover, no suitable models have been provided for seepage which is also a likely water infiltration mechanism when cladding deteriorates at the top of the pipe. Since developing mathematical models for these very complex phenomena goes beyond the scope of this thesis here we restrict our focus to experimental models of saturation dynamics.

Chapter III

3. BACKGROUND OF MICROWAVE EXCITATION AND PROPAGATION IN COAXIAL WAVEGUIDES

In oil pipelines, the pipe and metallic cladding form a large coaxial transmission line with the insulation acting as a dielectric which allows propagation of microwave signals along the length. In the following subsections, we discuss the theory involved in electromagnetic wave excitation and propagation in coaxial waveguides.

3.1. Maxwell's equations

The propagation of electromagnetic waves in waveguides is governed by the Maxwell's equation [17],

$$\nabla \cdot \mathbf{D} = Q, \quad (3.1)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (3.2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (3.3)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}. \quad (3.4)$$

where $\mathbf{D}$ is the electric flux density, Q is the free charge density, $\mathbf{B}$ is the magnetic flux density, $\mathbf{E}$ is the electric field, $\mathbf{H}$ is the magnetic field and $\mathbf{J}$ is the conduction current density. In the absence of conduction currents and free charges, harmonic oscillations at frequency

ω are therefore described by,

$$\nabla \cdot \mathbf{D} = 0, \quad (3.5)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (3.6)$$

$$\nabla \times \mathbf{E} = -j\omega\mathbf{B}, \quad (3.7)$$

$$\nabla \times \mathbf{H} = j\omega\mathbf{D}. \quad (3.8)$$

Equations (3.5) to (3.8) are used to formulate the characterisitic equations for electromagnetic wave propagation in waveguides. The time dependance of the form $e^{j\omega t}$ (i.e. monochromatic waves) is assumed and all the vector components are split into a transverse component(denoted by subscript t) and longitudinal component (denoted by subscript z). The Maxwell's equations then become,

$$\left\{ \nabla_t^2 + \frac{\partial^2}{\partial z^2} + \omega^2 \epsilon_o \mu_o \epsilon_r \mu_r \right\} E_z = 0, \quad (3.9)$$

$$\left\{ \nabla_t^2 + \frac{\partial^2}{\partial z^2} + \omega^2 \epsilon_o \mu_o \epsilon_r \mu_r \right\} H_z = 0. \quad (3.10)$$

Equations (3.9) and (3.10) represent the wave equations for any isotropic medium, including conducting media for arbitrary values of ϵ and μ as shown in Ref. [17]. Analytical solution for EMW propagation in coaxial waveguides is then derived from these equations on the application of the essential boundary conditions.

3.2. Analytical solution for a coaxial waveguide

A basic setup of a coaxial waveguide consists of two cylindrical conductors aligned along the z-axis with the space between them filled by a dielectric of permittivity, ϵ and perme-

ability, μ . The radii of the outer and inner conductors are denoted by a and b respectively. Monochromatic waves travelling in the z -direction are characterized by the function $e^{-j\beta z}$ and substituting $\partial^2/\partial z^2 = -\beta^2$ and $\omega^2\epsilon_o\mu_o\epsilon_r\mu_r - \beta^2 = k_t^2$, the wave equations (3.5) and (3.10) become,

$$(\nabla_t^2 + k_t^2) \begin{pmatrix} E_z \\ H_z \end{pmatrix} \equiv \left\{ \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + k_t^2 \right\} \begin{pmatrix} E_z \\ H_z \end{pmatrix} = 0. \quad (3.11)$$

where β is the axial wave number and k_t is the tangential wave number.

These equations are solved by the method of separation of variables which yields the equations for waves in the region $b < r < a$ as shown in pgs. 227-228 and 246 of Ref. [17] to obtain,

$$E_z = AJ_p(k_r r) + BY_p(k_r r) \sin(p\theta) e^{j\omega t} e^{-j\beta z}, \quad (3.12)$$

$$H_z = CJ_p(k_r r) + DY_p(k_r r) \begin{pmatrix} \cos p\theta \\ \sin p\theta \end{pmatrix} e^{j\omega t} e^{-j\beta z}. \quad (3.13)$$

where k_r is the radial wave number, J_p is a Bessel function of first kind of order p , and Y_p is a Bessel function of second kind of order p . The boundary conditions are now applied to these equations to determine the values of the arbitrary constants A , B , C and D and to obtain the characteristic equations for the TE and TM modes in a coaxial waveguide. The

boundary conditions to be considered are those at $r = a$ and $r = b$ and are listed below,

$$r = a : E_z = 0, \quad (3.14)$$

$$r = b : E_z = 0, \quad (3.15)$$

$$r = a : E_\theta = 0, \quad (3.16)$$

$$r = b : E_\theta = 0. \quad (3.17)$$

H_z is related to E_θ by the equation $k_t^2 E_\theta = \frac{-j\beta}{r} \frac{\partial E_z}{\partial \theta} + j\omega\mu_o\mu_r \frac{\partial H_z}{\partial r}$. Since $E_z = 0$ on $r = a$, $\partial E_z / \partial \theta = 0$, which leads to the requirement $\partial H_z / \partial r = 0$. Eq. (3.14) to (3.17) are substituted in the wave equations for a coaxial region [Eq. (3.12) and (3.13)] to derive the characteristic equations for electromagnetic wave propagation in coaxial waveguides. A detailed derivation of these equations is shown in Chapter IV of Waldron [17],

$$J_p(k_r a) Y_p(k_r b) - J_p(k_r b) Y_p(k_r a) = 0, \quad (3.18)$$

$$J'_p(k_r a) Y'_p(k_r b) - J'_p(k_r b) Y'_p(k_r a) = 0. \quad (3.19)$$

Eq. (3.18) and (3.19) represent the characteristic equations for the TM mode and TE mode respectively. The integers p and q are used to represent the distinct modes of propagation for coaxial waveguides, with the two series of modes having their own set of p and q modes: TM_{pq} and TE_{pq} .

These characteristic equations are implicit and can be solved numerically to obtain the dispersion curves for EMW propagation. To solve these equations for a particular mode (p, q) which exist in the coaxial waveguide, it is necessary to be able to determine the position of the q^{th} zero of any Bessel function, or its derivative, of order p . Assuming $\xi = mb$ and

defining $\gamma = a/b$, we get $ma = \gamma\xi$ which is substituted in Eq. (3.18) and (3.19) to give ξ as the q^{th} zero of the Bessel function of order p [11].

For any particular value of p and q , the phase constant β is given by,

$$\beta = \left(\frac{2\pi}{\lambda}\right) \sqrt{1 - \frac{\xi^2 \lambda^2}{4\pi^2 b^2}}. \quad (3.20)$$

The phase and group velocities for the different modes and their relationship to the phase constant is given by,

$$v_p = \frac{\omega}{\beta}, \quad (3.21)$$

$$v_g = \frac{\partial \omega}{\partial \beta}. \quad (3.22)$$

where v_p and v_g represent the phase and group velocities respectively. Using equations (3.21) and (3.22), the phase and group velocity dispersion curves can be plotted for any of the TE_{pq} and TM_{pq} modes. There exists another mode that propagates in coaxial waveguides which is fundamentally different from the TE and TM modes called the Transverse Electromagnetic mode (TEM) also referred to as the transmission line mode. As shown in Ref. [17], the TEM mode has its phase and group velocities equal to the speed of light at all frequencies and hence is non-dispersive.

Fig 3.1 shows the frequency dependant plot of the normalised phase and group velocity curves for a coaxial waveguide of dimensions $a=157.5\text{mm}$ and $b=80\text{mm}$ which mimics an oil pipeline. It is evident from the figure that the modes are divided into distinct families, such that the TE_{p1} mode family is spread over the lower frequencies, followed by the TE_{p2} and TM_{p2} families overlapping each other and so forth. The reasoning behind the separation of

FIG. 3.1: The dispersion curves for a coaxial waveguide of dimensions $a=157.5\text{mm}$ and $b=80\text{mm}$, which show the variation of the normalized phase and group velocities with frequency.

the mode families is facilitated by the plots of the modal field distributions as explained in Ref. [11]. In the following subsection we discuss the issues in guided wave inspection and reasoning behind the use of the TEM mode for inspection.

3.3. Transverse electromagnetic mode (TEM)

A major factor that affects the detectability of wet insulation during the guided wave inspection is the signal-to-coherent-noise-ratio (SCNR). Coherent noise refers to any deterministic signals that corrupt the signal of interest and cannot be removed by temporal averaging. A high SCNR increases the sensitivity of an inspection technique. There are two main sources of SCNR in guided wave inspection systems, the presence of spurious modes that propagate with the mode selected for inspection and the modal dispersion.

A wavepacket consists of a spectrum of frequencies, and each of these frequencies propagates at different phase velocities during dispersive propagation as shown in Fig 3.1. As a result, this wavepacket will undergo temporal spreading as it propagates, resulting in a loss of signal amplitude and an undesired increase in the duration of the wavepacket. Moreover the propagation of an inspection signal consisting of multiple modes leads to complex waveforms consisting of overlapping wavepackets which preclude the detection of pulses reflected from water volumes. Hence pure mode excitation of the TEM mode, which is non dispersive, is desirable.

3.4. Use of an array of antennas

Apart from the difficulties arising from dispersion and interference of different modes, a wide bandwidth of the inspection signals is required to achieve sufficient axial resolution in the output signal. However using a single antenna only frequencies upto the cutoff of the TE_{11} mode can be used as seen in Fig 3.1, to ensure only the TEM mode is excited. For 6" pipeline diameters that would correspond to a TE_{11} mode cutoff frequency of 60MHz resulting in a minimum resolvable distance of 2.5m, which is impractical.

The approach adopted by Jones et al. [11] was to use the frequency range up to the cutoff frequency of the TM_{02} which for 6" pipelines is around 2GHz as seen in Fig 3.1. A 2GHz bandwidth would lead to an axial resolution of 75mm, which would provide good spatial resolution for guided wave inspection of features within the waveguide. In [11], an excitation system was proposed which employed an array of antennas distributed regularly about the circumference of the waveguide to remove the spurious modes of the TE_{p1} mode family, which have cutoff below that of TM_{02} . The method exploits the difference in the symmetry of the axisymmetric TEM mode and non axisymmetric TE_{p1} modes. The basic principle involved is that, the TE_{p1} modes undergo p cycles of variation around the pipe circumference. According to the Nyquist sampling criterion, a mode that has p cycles, can be measured using $2p$ sampling points. The idea is therefore to use $2p$ antennas uniformly spaced around the circumference, where p is now the maximum expected order. By adding all the signals received by the antenna all the TE_{p1} modes are cancelled while the TEM mode is reinforced. As an example, for a 6" pipe the maximum circumferential order before the cutoff of TM_{02} is $p = 4$. Therefore it is sufficient to use 8 antennas as described in Ref. [11].

Chapter IV

4. REFLECTION COEFFICIENT ANALYSIS

As discussed in Sec.3.3 for practical long-range testing it is convenient to use the fundamental transversal electromagnetic mode (TEM) which is non-dispersive and travels at speed c/n where c is the speed of light in vacuum and n is the refractive index of the dielectric medium that fills the space between the internal and external conductors, i.e. the insulation material.

Scattering of the TEM mode from inhomogeneities within the dielectric such as a localized water volume can be studied using Maxwell's equations. Since dry insulation is transparent to the microwave signals, the electric field, $\mathbf{E}$, must satisfy the differential equation [18]

$$\nabla^2 \mathbf{E}(\mathbf{s}, \omega) + k^2 \mathbf{E}(\mathbf{s}, \omega) = -F(\mathbf{s}, \omega) \mathbf{E}, \quad (4.1)$$

where ∇^2 denotes the Laplace operator, $\mathbf{s}$, is the position vector of a point inside the insulation, ω , the angular frequency, k , the wavenumber in vacuum, and $F(\mathbf{s}, \omega)$ the scattering potential defined as

$$F(\mathbf{s}, \omega) = k^2 [n^2(\mathbf{s}, \omega) - 1], \quad (4.2)$$

where $n(\mathbf{s}, \omega)$ is the refractive index. The scattering potential is used to model the wet insulation through $n(\mathbf{s}, \omega)$ which causes F to vanish outside the wet volume ($n = 1$ in the dry insulation) and leads to maxima inside the 100% saturated regions of the insulation where $n \approx 8.9$ (here we use the refractive index of water [19] assuming that the insulation

FIG. 4.1: Coaxial waveguide with a step discontinuity in the refractive index, n . The TEM mode is incident on the interface between the two dielectric sections and the sudden change in n results in a partial reflection of the mode.

is highly porous). Inside the transition region the refractive index is expected to vary continuously between 1 and 8.9 depending on the water saturation level.

An analytical solution for eq. (4.1) can be obtained for the ideal case in which the saturation front is axi-symmetric and causes a step discontinuity in the refractive index as shown in Fig. 4.1. Letting A be the amplitude of the incident TEM mode and B the amplitude of the reflection from the discontinuity, the reflection coefficient, R , is given by the well known relationship

$$R = \frac{B}{A} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \quad (4.3)$$

where Z_i is the electromagnetic impedance defined as [17]

$$Z_i = \frac{1}{2\pi n_i} \ln\left(\frac{a}{b}\right) \sqrt{\frac{\mu_0}{\varepsilon_0}}, \quad (4.4)$$

where a and b are the outer and inner radii of the coaxial waveguide, and μ_0 and ε_0 the

permeability and permittivity constants in vacuum. The subscripts 1 and 2 are used to refer to the dry and wet insulation, respectively. Substituting eq. (4.4) into eq. (4.3), the reflection coefficient can be expressed as a function of the refractive index only

$$R = \frac{B}{A} = \frac{1 - n_2}{1 + n_2}, \quad (4.5)$$

Using $n_2 \approx 8.9$ expression (4.5) leads to $R = 80\%$ which is to be considered as an upper bound for the reflection coefficients that can be measured under realistic field conditions. In fact, it can be expected that in practical applications water will not be distributed all around the pipe circumference leaving some sections of the insulation annulus dry. These can convey a significant fraction of the energy of the incident mode pass the water volume and hence reduce the strength of the reflected signal by energy conservation. As shown in Ref. [11] there exists an almost linear relationship between the area of the annulus cross-section saturated by water, A_S , and the reflection coefficient

$$R \approx 0.8 \frac{A_s}{\pi(a^2 - b^2)}. \quad (4.6)$$

Relationship (4.6) is valid for a step-like transition between dry and wet insulation and assumes that the saturation front is planar and orthogonal to the pipe axis. However, in practice the saturation front may be irregular and at an angle relative to the pipe axis as shown in Fig. 4.2. This results in a complex spatial distribution of the refractive index which is likely to cause a deviation from the linear relationship between R and the saturated cross-sectional area A_S and may lead to lower reflection coefficients than those predicted by eq. (4.6). The extent of these changes is mainly dependent on the length scale characterizing

FIG. 4.2: Wet insulation is likely to be localized in a complex 3-D volume. Depending on the characteristic length scale of the water volume, Δ , relative to the wavelength, λ , of the TEM mode the reflection coefficient is not necessarily proportional to the largest saturation cross-section A_s .

the irregularities of the saturation front, Δ , relative to the wavelength, λ , of the incident TEM mode. Here, λ is the wavelength in the dry insulation (essentially the same as the wavelength in vacuum) and Δ combines both the scale of the geometrical features of the saturation front as well as the extent of any possible saturation gradient.

In order to quantify the effect of the Δ/λ ratio it is observed that the wavelength of the TEM mode must be greater than twice the insulation thickness. This is necessary to maintain the bandwidth of the incident signal below the cutoff frequency of the second axi-symmetric mode, TM_{02} , and hence avoid signal contamination from unwanted modes [11]. As a result, at the signal center frequency the wavelength is about four times the insulation thickness. This suggests the applicability of a long-wavelength approximation that homogenizes the radial variations of the refractive index leading to an effective index, n_{eff} , which is constant along the radius and only depends on the axial and circumferential position.

In first approximation the circumferential and axial dependence of n_{eff} can be treated

separately and the reflection coefficient obtained by adapting eq. (4.6) to

$$R \approx R_S \frac{A_s}{\pi(a^2 - b^2)}, \quad (4.7)$$

Here, R_S is the reflection coefficient for an ideal transition region from dry to fully saturated insulation that extends to the entire insulation annulus [$A_s = \pi(a^2 - b^2)$] and covers an axial length Δ . The transition is axi-symmetric relative to the waveguide axis with the same n_{eff} profile for any radial plane.

Figure 4.3 presents numerical simulations performed with the method outlined in the Appendix and shows R_S as a function of the transition length relative to the wavelength for four different n_{eff} profiles described by

$$n_{eff}(z) = 1 + (n - 1)h(z/\Delta), \quad (4.8)$$

where $h(z/\Delta)$ is the profile function and $n = 8.9 + i0.2$ (corresponding to permittivity $\varepsilon = 78.60 + i3.51$) is the complex refractive index of water at room temperature at 1 GHz [20]. The profile functions, which are shown in Fig. 4.3(a), correspond to linear, $h(\xi) = \xi$, quadratic, $h(\xi) = \xi^2$, and cosine, $h(\xi) = 0.5[1 - \cos(\pi\xi)]$, transitions. An additional profile function termed conical transition is given by

$$h(\xi) = \frac{a - b}{a + b}\xi^2 + \frac{2b}{a + b}\xi, \quad (4.9)$$

and is used to describe a conical saturation front with apex pointing toward the incident TEM mode and axis parallel to the pipe (a schematic of this configuration is given later in Fig. 6.1). For this configuration, the refractive index undergoes a step discontinuity in the

FIG. 4.3: Simulated reflection coefficients for axi-symmetric gradual transitions from dry to 100% water saturated insulation. (a) Four different n_{eff} profiles along the transition length Δ ; (b) Reflection coefficients at 1 GHz corresponding to the profiles in (a) as a function of the transition length relative to the wavelength, λ . (dotted curves) linear transition; (light gray curves) quadratic transition; (dark gray curves) cosine transition; (black curves) conical transition; (squares) experimental data for the conical transition.

radial direction. However, based on the effective medium argument for every axial position, z , we can homogenize n by taking its area-weighted average across the insulation annulus, i. e.

$$\begin{aligned}
 n_{eff}(z) &= \frac{A_D(z) + nA_S(z)}{\pi(a^2 - b^2)} = 1 + (n - 1) \frac{A_S(z)}{\pi(a^2 - b^2)} \\
 &= 1 + (n - 1) \left(\frac{a - b}{a + b} \xi^2 + \frac{2b}{a + b} \xi \right),
 \end{aligned} \tag{4.10}$$

where A_D is the dry portion of the insulation annulus area. This model will be later validated against experimental data in Sec. 6

Analysis of Fig. 4.3(b) reveals several important phenomena. For all the different transition profiles the reflection coefficient decreases as the transition length increases, which is to be expected since the transition becomes more gradual. Moreover, the curves exhibit

the presence of ripples which are due to constructive and destructive interference of waves reverberating inside the transition length. As Δ increases the ripples become less apparent since the interference effects weaken due to increased damping of the reverberations caused by higher signal attenuation.

When Δ is small compared to the wavelength ($\Delta/\lambda < 0.25$) the shape of the profile function has little effect on the reflection coefficient. In this case, since λ is greater than Δ the incident mode has low sensitivity to the saturation front irregularities and the reflection coefficient tends to the value predicted by eq. (4.6), this being consistent with the experiments performed in Ref. [11] where the saturation front was shaped as a torus with tube radius $\Delta \approx \lambda/10$.

For large values of Δ the shape of the profile function begins to affect the reflection coefficient. In particular, the slope of the profile function at the beginning of the transition region determines the strength of the reflection. When the slope is small (quadratic and cosine transitions), the incident TEM finds little resistance and penetrates into the transition region without generating a significant reflected signal. On the other hand, a discontinuous change of the slope at the entry point (linear and conical transitions) results in higher amplitude reflections.

It should be stressed that in the calculations shown in Fig. 4.3(b) the function $h(\xi)$ used to describe the variation of the refractive index within the transition zone according to eq. (4.8) is not necessarily equal to the water volume fraction $\varphi(\xi)$. The two functions can however be related by a so-called mixing law as in the case of binary mixtures. Mixing laws assume that the effective refractive index of the mixture is only dependent on the indices of the two species in the mixture and their volume fractions, thus neglecting any coupling effects. However, even under this approximation no universal mixing law exists that can be

applied to all binary mixtures and instead a wide array of semi-empirical relationships has been proposed in the literature; Ref. [21] conveniently lists 10 of the most common laws. The Arago-Biot law postulates a linear relationship between n_{eff} and φ and corresponds to the condition

$$n_{eff}(z) = 1 + (n - 1)\varphi(z/\Delta), \quad (4.11)$$

which by comparison with eq. (4.8) implies that $h(\xi) = \varphi(\xi)$. This model has been widely employed to predict the refractive index of wet soil [22] and is the model that we have adopted to study the conical transition case.

Newton's mixing law has been proposed to study water saturation in concrete see, for instance, Ref. [23] and assumes linearity between the effective permittivity and the volume fraction, or in terms of refractive indices

$$n_{eff}^2(z) = 1 + (n^2 - 1)\varphi(z/\Delta). \quad (4.12)$$

Comparing eq. (4.12) with (4.8) it is apparent that under Newton's model a nonlinear relationship exists between $h(\xi)$ and $\varphi(\xi)$. Moreover, for the same water volume fraction, Newton's model leads to higher refractive index than the Arago-Biot model and hence to smaller impedance which ultimately leads to stronger reflections. The lack of an universal model for binary mixtures suggests that different mixing laws will apply to different types of insulation materials and for each material the permittivity profiles shown in Fig. 4.3(a) will have to be mapped onto the corresponding water volume fraction using the appropriate mixing law. In general it can be expected that the refractive index will increase with the

water volume fraction.

Overall the results shown in Fig. 4.3 suggest that if the transition occurs on a length scale comparable to the insulation thickness (i. e. $\Delta/\lambda \leq 0.25$) the reflection coefficient reduction due to saturation gradients will be within 50% of the ideal reflection obtained for an abrupt transition with saturation front orthogonal to the incident TEM mode. In the next chapters the extent of realistic transition regions are characterized through model experiments.

Chapter V

5. EXPERIMENTAL SETUP

The setup used in the experimental study was similar to that described in Ref. [11] and is shown in Fig. 5.1. A 3.2 m long section of a 6" diameter pipe with 3" thickness insulation was simulated using 24 gauge galvanized G60 steel ducting. Ducting is significantly lighter than pipes and therefore better suited for laboratory experiments. Moreover, at typical microwave frequencies the skin depth in steel is less than $10\text{ }\mu\text{m}$ meaning that from an electromagnetic perspective ducting effectively behaves as a thick pipe. The diameter of the inner ducting was 160 mm while the diameter of the outer ducting mimicking the cladding was 315 mm. No insulation was used to fill the gap between the two ducting sections since it has been previously shown that most insulation materials are almost transparent to microwave radiation [11].

A Precision Network Analyzer (PNA) from Agilent (model N5227A with a frequency range from 10 MHz to 67 GHz) was used to generate a microwave signal with bandwidth from 500MHz to 1.7GHz - the upper cutoff was chosen to avoid signal contamination from higher order modes. The signal from the PNA was routed to an array of eight identical antennas through an 8-way power combiner/divider. The antennas consisted of brass rods 15 mm diameter, 68 mm length soldered to the inner conductor of SMA bulkhead connectors. Non-conducting polyurethane plastic was used to reinforce the solder joint against the stress resulting from the weight of the antenna. Electrical contact between the outer conductor of the SMA connectors and the cladding was ensured by bolting the connectors to the cladding through small holes. The antennas were at a 10 mm stand off distance from the inner pipe with no electrical contact.

FIG. 5.1: Microwave experimental setup. The signal from a network analyzer is routed to an array of eight antennas through an 8-way power divider/combiner. The array launches the TEM mode within the gap formed by two concentric ducting sections simulating the insulation layer. The same array is then used to detect the reflected signal which is subsequently displayed on the analyzer in the form of an echogram.

The PNA measured the S_{11} parameter and displayed the signal in the form of a real-time echogram using time domain reflectometry.

Different transition regions and saturation gradients were produced using phenolic foam (florist foam) blocks partially or fully saturated with water. Although the hydraulic properties of the foam are likely to be different from those of the insulation materials used in practice, the phenolic foam was chosen because it is highly porous (94% porosity) and permeable resulting in rapid saturation dynamics which is highly desirable when studying a wide range of absorption mechanisms. Moreover, it can easily be cut into different shapes to simulate relatively complex saturation fronts. Finally, in its dry state the foam is completely transparent to microwave radiation like most insulation materials.

Chapter VI

6. EXPERIMENTAL RESULTS

Four sets of experiments were conducted to measure reflection coefficients from various water volumes obtained from fully saturated foam blocks or blocks exposed to water uptake and seepage. The different test configurations and the corresponding microwave experimental results are discussed in the following subsections

6.1. Conical saturation front

The idealized conical front modeled in Sec. 4 was produced by securing several wedge-shaped foam blocks around the circumference of the inner ducting as shown in Fig. 6.1(a); the blocks were 100% water saturated and were positioned around the center of the ducting. Two sets of blocks with transition lengths $\Delta = 80$ mm and $\Delta = 250$ mm were used. Larger transition lengths could not be tested since they require sharper apex angles which cause the foam to break during manufacture of the wedges. Figure 6.1(b) compares the echograms measured before and after introducing the 80 and 250 mm length blocks. The time axis has been converted to distance using $c/2$ as a scaling factor. The pulse around $d=0$ m is due to the reflection of the microwave signal at the point where the feeding coaxial cables meet the antennas and although it does not carry information about the status of the insulation it provides a convenient means to locate the position of the reflectors relative to the array.

The baseline signal shows a large pulse at distance $d = 3.2$ m corresponding to the reflection from a metallic cap placed at the end of the ducting section and acting as a 100% reflector. The signals measured after inserting the saturated blocks show a reflected pulse at around $d = 1.6$ m which is not present in the baseline signal and is due to the conical

FIG. 6.1: Conical saturation front. (a) Arrangement of foam wedges around the inner ducting; (b) Reflection signals measured without foam (thick black), with saturated blocks of length $\Delta=80$ mm (light gray), and length $\Delta=250$ mm (dark gray).

saturation front. For these signals the reflection from the end cap is highly attenuated due to the large amplitude attenuation of the signal transmitted through the water volume as well as a partial reflection of the incident energy by the saturation front. To evaluate the reflection coefficient from the saturation front, the amplitude of the pulse reflected from the front is divided by the amplitude of the end-cap reflection of the baseline signal. For the two transition lengths $\Delta = 80$ mm and $\Delta = 250$ mm this leads to $R=41\%$ and $R=18\%$, respectively. These values are in good agreement with the analytical predictions as shown in Fig. 4.3(b) where also the experimental value of the reflection coefficient from a saturation front orthogonal to the incident wave ($\Delta/\lambda=0$) is given.

The experiments therefore provide validation of the simple analytical model given in Sec. 4 and confirm that the length of the transition region, Δ , relative to the wavelength of the incident TEM mode is a driving parameter determining the strength of the reflection from wet insulation.

FIG. 6.2: Experimental simulation of saturation gradients. (a) Saturation gradient produced by capillary water rise in a foam block partially immersed in water showing a 100% saturated section followed by a transition region of length $\Delta \sim 40$ mm; (b) Configuration of the block inside the coaxial waveguide showing the position of the saturation gradient relative to the incident TEM mode.

6.2. Saturation gradient

In the previous experiment the foam wedges were 100% water saturated thus causing a discontinuous transition through the conical surface. To study the effect of actual saturation gradients a foam brick $95 \times 75 \times 100$ mm was placed in a water reservoir and left to absorb water until no noticeable changes in the saturation front could be observed. As discussed in Ch. 2 after an initial rapid advance of an abrupt water front, the capillary raise led to a saturation gradient over a transition region of $\Delta \sim 40$ mm as shown in Fig. 6.2(a). The total water volume absorbed by the foam block was 400 ml as it was inferred by measuring the weight of the brick before and after water uptake.

The block was subsequently placed inside the coaxial waveguide as shown in Fig. 6.2(b), with the transition region pointing towards the incident TEM mode to monitor the reflection coefficient from the saturation gradient at 20 min intervals. The block completely filled the annulus in the radial direction and covered 100 mm in the circumferential direction leading to a saturated region that occupied 13% of the annulus cross sectional area. Figure 6.3

FIG. 6.3: Monitoring experiment showing the reflection coefficient for the saturation gradient shown in Fig. 6.2.

provides the reflection coefficient as a function of time over a period in excess of two weeks. During this time the reflection coefficient decreased by about 2% due to the effect of gravity which caused a slow downward water flow decreasing the extent of the water volume in the radial direction and hence reducing the saturation cross sectional area A_S . Despite this effect the reflection coefficient is very close to that obtained when a fully saturated block of the same dimension was placed inside the waveguide as shown by the dotted line in Fig. 6.3.

From this experiment it can be concluded that the extent of the transition region caused by water uptake under capillary rise is small compared to the wavelength ($\Delta/\lambda \sim 0.13$) and therefore the saturation gradient is seen as a sharp transition from the incident wave. As a result, eq. (4.6) still provides a valid model predicting $R = 10.4\%$ which is in very good agreement with the experimental value of 10.7% observed at early times.

6.3. Capillary rise and seepage monitoring

FIG. 6.4: Experimental setup used to perform: (a) Capillary rise monitoring; (b) Seepage monitoring.

In practical applications water absorption inside the insulation may be driven by capillary rise of water accumulated at the bottom of the cladding or seepage from gaps in the cladding at the top of the pipe. The shape of the saturation front and the extent of the saturation gradient vary throughout the absorption process and will affect the amplitude of the reflected microwave signal. To determine the sensitivity of microwave signals to the early stages of water absorption, continuous monitoring tests were conducted during capillary rise and seepage experiments according to the setups shown in Fig. 6.4.

To simulate capillary rise a foam block was cut into the shape of a $135 \times 60 \times 100$ mm brick with a $20 \times 25 \times 100$ mm protrusion at the center of the block base and spanning across the entire width of the block. The block was placed inside the waveguide at its center as

FIG. 6.5: Reflection coefficient from absorbed water as a function of time during capillary rise: (a) Early stages of the water uptake; (b) Long term monitoring towards equilibrium.

shown in the diagram of Fig. 6.4(a). The protrusion extended into a water reservoir through an aperture in the cladding and was used to simulated a strip water source 20 mm wide in the direction of the incident wave and 100 mm length in the circumferential direction. The water level of the reservoir was maintained constant to ensure that water was continuously fed through the protrusion.

For the seepage experiment a $160 \times 75 \times 100$ mm foam brick was placed inside the waveguide at its center as shown in Fig. 6.4(b) and a continuous water stream was injected with a small diameter feedline at a rate of approximately 50 ml/min through an aperture in the cladding. In both the capillary rise and seepage experiments the total volume of water absorbed by the foam was obtained by weighing the foam before and after water absorption.

Microwave signals were acquired and stored at 5 sec intervals for the first 10 minutes and subsequently every 2 minutes. To compensate for backscattering caused by the aperture in the cladding used to allow water into the foam blocks, a baseline measurement was performed to estimate the amplitude of the pulse reflected from the aperture without foam. This value which was 0.1% of the end cap reflection was subtracted from the reflection coefficient from the absorbed water. It should be noted that water infiltration in the insulation of actual pipelines is caused by narrow gaps of a few millimeters in width. The width is therefore between one to two orders of magnitude smaller than the TEM wavelength and the gaps result in very negligible backscattering and minimal signal loss due to leakage in the surrounding space.

Figure 6.5 shows the reflection coefficient as a function of time for the capillary rise experiment. Photograms of the waterfronts at the time instances marked by the labels are shown in Fig. 6.6. These were obtained with a foam block identical to that used in the microwave experiment when it was exposed to the same capillary rise conditions outside the waveguide - this was necessary since the cladding prevents the visual inspection of the blocks inside the waveguide. Due to the shape of the block's protrusion, the saturation front can be approximated to a cylindrical surface with generatrix parallel to the length of the protrusion as shown in Fig. 6.6. The shape of the saturation front was therefore monitored on one side of the block with an AVT GuppyPro F-201 Firewire camera which captured and

FIG. 6.6: Photograms of the water front corresponding to the time instances indicated in Fig. 6.5.

stored photograms at a 0.1 Hz rate. By synchronizing the microwave signals with the optical measurements it was then possible to correlate the reflection coefficient to the corresponding saturation front shape.

FIG. 6.7: Reflection coefficient from absorbed water as a function of time during seepage.

From the analysis of Figs 6.5 and 6.6 it can be observed that for small times, capillary rise leads to a preferential water infiltration in the radial (vertical) direction. This is accompanied by a rapid increase in the saturated cross section A_S which causes an increase in the reflection coefficient. Around point (b) the speed at which the saturation front advances in the radial direction decreases significantly in a similar fashion to the phenomenon observed around the equilibrium height predicted by the Washburn model. The front now starts to expand in the horizontal plane leading to a shallower inclination angle of the saturation front relative to the incident wave which causes a reduction in the reflection coefficient, points (c) and (d). Around point (e) the saturation front reaches the edge of the block and water starts again to advance in the radial direction guided by the free surface of the block. Under this condition, microwave reflection is governed by the saturated cross-sectional area directly exposed to the incident wave where an abrupt dry-wet transition occurs. As more water is absorbed the area increases and so does the reflection coefficient. At point (g) the base

of the block is uniformly saturated and a saturation gradient continues to slowly advance the water front in the radial direction until equilibrium is reached around point (j) where the reflection coefficient stabilizes around 3.5%. Beyond point (j) the saturation dynamics appears to stabilize with no detectable changes in the water distribution. The total amount of water absorbed by the block was 500 ml which completely saturated a 30 mm thickness section at its base. As a result, the saturation cross sectional area was $A_S = 30 \times 100 = 3,000$ mm² corresponding to 5% of the insulation annulus cross section. For this value of A_S the reflection coefficient predicted by eq. (4.6) is $R = 4\%$ which is in good agreement with the experiments.

The variation of the reflection coefficient monitored during the seepage experiment is shown in Fig. 6.7 with photograms of the saturation front at the points indicated by the labels being given in Fig. 6.8.

Due to symmetry, the saturation front is a surface of revolution around the normal to the top surface of the block passing through the injection point. Therefore, while in the microwave test water was injected at the center of the block (this approximates realistic field conditions), injection was performed on one side of the block when monitoring the shape of the front with the camera. In the latter case only 50% of the total water volume injected during the microwave test was used.

From Figs 6.7 and 6.8 it emerges that the saturation front rapidly grows in the radial (vertical) direction until it reaches the base of the block in contact with the inner ducting, points (a)-(d). In this time the saturated cross-sectional area increases monotonically and so does the reflection coefficient. As more water is added the front starts to expand laterally, (e) and (f), retaining a quasi-cylindrical shape. Under seepage therefore the saturation front is oriented orthogonally to the incident wave resulting in the most favorable condition

FIG. 6.8: Photograms showing the saturation front during seepage and corresponding to the points indicated in Fig. 6.7.

that maximizes microwave reflection. The total volume of injected water was 250 ml with the 100% saturation occurring within a cylindrical volume of about 70 mm diameter and extending across the block thickness (75 mm). This corresponds to $A_S = 75 \times 70 = 5,250$ mm² which through eq. (4.6) gives $R = 7\%$ again in good agreement with the experiments.

Chapter VII

7. CONCLUSIONS

The use of guided microwave has recently been proposed as a long-range inspection/-monitoring method to detect sections of wet insulations in pipelines. High sensitivity has been reported for idealized water volumes characterized by an abrupt transition from dry to 100% water saturation. The question however arises whether more gradual transitions may be expected under realistic field conditions and if so how these can affect the sensitivity of microwaves.

The determination of realistic transition regions inside the insulation is challenging due to the lack of detailed field observations. Moreover, existing mathematical models for saturation dynamics are limited to mono-dimensional problems and depend on a large number of empirical parameters. As a result, currently it is not possible to use numerical simulations to predict realistic water saturation paths in the insulation.

7.1. Summary of Findings

In this thesis, an attempt has been made to model more realistic saturation scenarios through model experiments performed with phenolic foam which is a highly permeable and porous material. It has been shown that the amplitude of microwave reflections is mainly dependent on the wavelength of the incident signal, λ , the cross-sectional area, A_S , of the insulation annulus saturated by water, and a characteristic transition length Δ . The latter captures the scale of the spatial variations of the actual saturation front relative to the ideal case of an abrupt transition across a planar front orthogonal to the incident wave and for which the reflection coefficient is proportional to A_S only.

It is found that the effect of the transition length becomes significant when Δ is greater than $\lambda/4$. Under this condition the reflection coefficient is more than 50% lower than that observed for an abrupt transition with the same saturation cross-sectional area A_S . Importantly, $\lambda/4$ must be approximately the same as the insulation thickness in order to avoid signal contamination from higher order guided modes. Therefore, in practical testing the transition length has to be greater than the insulation thickness to adversely impact the sensitivity of microwave inspections.

Seepage of water from gaps in the cladding or capillary rise from water accumulated at the bottom of the cladding are two possible mechanism that can lead to CUI and which have been studied in this paper. Regardless of the absorption mechanism, experiments have shown that after an initial rapid propagation of an abrupt saturation front, saturation gradients develop in the proximity of the front leading to a transition layer where water saturation varies gradually from 100 to 0%. However, the thickness of the transition layer was found to be small compared to the insulation thickness and the presence of a saturation gradient did not affect microwave reflectivity.

Different saturation front geometries were observed depending on whether water absorption was due to seepage or capillary rise. Seepage led to ideally oriented saturation fronts with minimal Δ and large A_S which grew monotonically as water was injected and lead to a direct water path from the outer cladding to the pipe. Such a path was not observed in the case of capillary rise where the water front reached an equilibrium height at about half the insulation thickness. After reaching equilibrium the saturation front continued to expand horizontally at constant maximum height causing an increase in Δ and hence a reduction in the reflection coefficient. This trend was however reverted when the front reached the edge of the foam block. Here, the free surface of the block acted as a guide that advanced

the saturation front towards the pipe and produced a new, abrupt saturation front orthogonal to the incident signal. The new front was therefore configured for optimal microwave sensitivity allowing the reflection coefficient to increase as more water was absorbed. The behavior observed at the free surface of the foam block is of practical importance because in actual pipelines the insulation layer consists of short shell sections placed next to each that form small gaps at regular intervals along the pipe. The gaps could indeed be preferential paths for water migration from the cladding to the pipe thus providing ideal orientation of the saturation fronts for microwave detection.

7.2. Future Work

There are several lines of research arising from this work which could be pursued.

Firstly the experiments performed in the thesis use phenolic foam as insulation as opposed to Rockwool, Polyurethane or Glass foam which are prominent in industrial applications. Secondly the experiments were performed in laboratory conditions at room temperatures which makes it unclear as to how the high working temperature of the pipelines would affect water infiltration in the insulation. Further research is therefore essential to study the performance of the technique under realistic field conditions. For this purpose, rugged inspection system is needed. In fact, the PNA used in this study is not suitable for field deployment. Similarly the antenna system and the splitter require an improved design in order to survive harsh field conditions.

Another research venue that should be pursued is the direct detection of corrosion product. As corrosion progresses, metal oxides build up on the surface of the pipe. Some of the oxides are transported by water flow and dispersed inside the insulation giving it a rusty appearance. The oxides may exhibit electrical and magnetic properties that could result in the

reflection of microwaves in a similar fashion to water. Indeed, preliminary tests performed by depositing small volumes of rust product on the inner pipe of the setup used in this study have shown that partial microwave reflection occurs. Future work should therefore try to address the reflection strength as a function of the oxides chemical composition and its distribution inside the insulation.

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Appendix A: Simulation of microwave backscattering

FIG. A.1: Discretization of the transition region used to predict the reflection coefficient from an arbitrary refractive index profile with the input impedance method.

In order to determine the reflection coefficient from an arbitrary refractive index profile $n_{eff}(z)$ the transition length, Δ , is divided into $N - 1$ small equal intervals of length $\delta = \Delta/(N - 1)$ according to Fig. A.1. It is then assumed that the refractive index of the k -th element centered at position $z = z_k$ is constant and equal to $n_{eff}(z_k)$. Under this assumption the transition region can be considered as a layered medium and the reflection coefficient estimated using the input impedance method outlined in [24] for a plane wave incident on a planar system of layers. Letting $Z_{in}^{(N)}$ be the input impedance of the system of $N - 1$ layers the reflection coefficient is given by the well known expression

$$R = \frac{Z_{in}^{(N)} - Z_{dry}}{Z_{in}^{(N)} + Z_{dry}}, \quad (\text{A.1})$$

where Z_{dry} is the impedance of dry insulation. The impedance $Z_{in}^{(N)}$ is calculated from the impedances of each layer, Z_k , given by

$$Z_k = \frac{1}{2\pi n_{eff}(z_k)} \ln\left(\frac{a}{b}\right) \sqrt{\frac{\mu_0}{\varepsilon_0}}, \quad (\text{A.2})$$

through the recursive formula

$$Z_{in}^{(k)} = \frac{Z_{in}^{(k-1)} - iZ_k \tan v_k \delta}{Z_k - iZ_{in}^{(k-1)} \tan v_k \delta} Z_k, \quad (\text{A.3})$$

where $v_k = \omega n_{eff}(z_k)/c$ is the wavenumber inside the k -th layer. To obtain $Z_{in}^{(N)}$, formula (A.3) is applied $N - 1$ times starting from layer 2 with the initialization condition $Z_{in}^{(1)} = Z_1$. This approach was employed by Jones in Ref. [25] and the reflection coefficient was simulated for axisymmetric water volumes as a function of the corresponding transition length.

The MATLAB scripts to implement this method are shown in Appendix B.

Appendix B: MATLAB Scripts

MATLAB script to generate the plot of simulated reflection coefficients for axisymmetric gradual transitions from dry to 100% water saturated insulation.

```
1 clear, clc, close all

2 %Pipe radius [m]

3 b=80e-3;

4 %Cladding radius [m]

5 a=157.5e-3;

6 %Center frequency

7 f=1e+9;

8 %Transition length [m]

9 Delta=[0:0.001:1.2];

10 %Delta=0.25

11 nDelta=length(Delta);

12

13 %Vacuum permittivity

14 e0=8.854187817e-12;

15 %Vacuum permeability

16 m0=4*pi*1e-7;

17

18 %Permittivity in water according to Debye model
```

```

19 e_s=81;

20 e_inf=5.6;

21 tau=25*1e-12;

22 e_r=e_inf+(e_s-e_inf)/(1+2*i*pi*f*tau)

23

24 %Speed of light

25 c_air=1/sqrt(e0*m0);

26 %Wavelength in vacuum

27 lambda=c_air/f;

28 %wavenumber in vacuum

29 k_air=2*pi/lambda;

30 %Impedence of the dry insulation

31 Z_air=1/2/pi*log(a/b)*sqrt(m0/e0);

32 %Impedence of the 100% saturated insulation

33 Z_wet=Z_air/sqrt(e_r);

34

35

36 for j=1:nDelta

37 [ e_A, e_L, e_Q, e_C, dx,x] = PermittivityFunction( e_r,lambda,Delta(j),a,b );

38

39 [ R_A(j) ] = ReflectionCoefficient( e_A,k_air,Z_air,Z_wet,dx);

40 [ R_L(j) ] = ReflectionCoefficient( e_L,k_air,Z_air,Z_wet,dx);

41 [ R_Q(j) ] = ReflectionCoefficient( e_Q,k_air,Z_air,Z_wet,dx);

```

```

42 [ R_C(j) ] = ReflectionCoefficient( e_C,k_air,Z_air,Z_wet,dx);

43

44 end

45

46 figure

47

48 plot(Delta/lambda,abs(R_A),'k')

49 hold on

50 plot(Delta/lambda,abs(R_L),'k:')

51 plot(Delta/lambda,abs(R_Q),'k--')

52 plot(Delta/lambda,abs(R_C),'g')

53 ylim([0 1])

54 xlim([0 4])

55

56 plot(0.25/lambda,18.07/100,'sk',0.08/lambda,41.12/100,'sk',0.001/lambda,80.9/100,'sk');

57

58 figure

59 plot(x,real(sqrt(e_A)),'k')

60 hold on

61 plot(x,real(sqrt(e_L)),'k:')

62 plot(x,real(sqrt(e_Q)),'k--')

63 plot(x,real(sqrt(e_C)),'g')

```


Discretization of the transition layer and computation of the impedance profile across each transition zone.

```

1 function [e_A, e_L, e_Q, e_C dx1,x] = PermittivityFunction( e_r,lambda,Delta,a,b )
2 %Need to take the conjugate to be consistent with Brekhovskikh formulation
3 e_r=conj(e_r);
4 %Transition layer discretization
5     %Wavelength in saturated water
6     lambda=lambda/sqrt(real(e_r));
7     %Elementary layer thickness
8     dx=lambda/10;
9     %Calculate the number of layers
10    N=fix(Delta/dx);
11    %Update the vlaue of dx to be consistent with N
12    dx1=Delta/N;
13    %Build the vecort x/Delta
14    x=( [0:N-1]'*dx1+dx1/2)/Delta;
15    %Build the impedance profile across the transition zone
16    e_A=1+(e_r-1)*((a-b)/(a+b)*x.^2+2*b/(a+b)*x); %Cone shape
17    e_A=(1+(sqrt(e_r)-1)*((a-b)/(a+b)*x.^2+2*b/(a+b)*x)).^2; %Cone shape
18    e_L=(1+(sqrt(e_r)-1)*x).^2; %refraction index linear variation
19    e_Q=(1+(sqrt(e_r)-1)*x.^2).^2; % refraction index quadratic variation
20    e_C=(1+(sqrt(e_r)-1)*0.5*(1-cos(pi*x))).^2; %refraction index cos step

```

```

21     %e_C=(1+(sqrt(e_r)-1)*(sin(pi*x/2))).^2; %refraction index cos step
22 end

```

Generating the simulated reflection coefficients.

```

1 function [ R ] = ReflectionCoefficient( e,k_air,Z_air,Z_wet,dx )
2 %Calculate the index of refraction
3 n_indx=sqrt(e);
4 %Claculate the impedance of each layer
5 Zn=Z_air./n_indx;
6 %Calculate the complex wavenumber in each layer
7 k=k_air*n_indx;
8
9
10
11 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
12 %%%%%%% From now follow Brekhovskikh convention %%%%%%%%%%%%%%%%%%%
13
14 %Initialize the impedance of medium 1 (this is the half space opposite
15 %to the incident wave)
16 Z_prev=Z_wet;
17
18 %number of layers

```

```

19     N=length(e);

20

21     for j=N:-1:1

22         Z_new=(Z_prev-i*Zn(j)*tan(k(j)*dx))/(Zn(j)-i*Z_prev*tan(k(j)*dx))*Zn(j);

23         Z_prev=Z_new;

24     end

25     R=(Z_prev-Z_air)/(Z_prev+Z_air);

26 end

```