Numerical modeling for terahertz testing of non-metallic pipes

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ABSTRACT
In the oil and gas industry, safety and operational efficiency at production sites are of paramount importance. A reliable non-destructive testing technology for non-metallic pipes has a high potential financial impact, since it may facilitate the replacement of metallic pipes with non-metallic ones. This article features a perspective and future trends in the field of terahertz sensing technology. Importantly, several numerical simulations that illustrate many exciting potential applications for this emerging technology are described. These range from underground detection of spilt liquids and the content of pipes to the detection of cracks in plastic pipes using both frequency-domain and time-domain finite-element simulations.

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I. INTRODUCTION
Oil and gas (O&G) firms face critical issues in the inspection of metallic assets such as pipes, tanks, and vessels. Corrosion of metallic assets leads to the largest expenditure in maintenance and inspection as it leads to leakage and safety concerns. Corrosion in oil and gas operations is generally caused by water, carbon dioxide (CO₂), and hydrogen sulfide (H₂S) and may be aggravated by microbiological activity. This results in environmental hazards, safety concerns, and loss of production through downtime for maintenance and repair. For this reason, deploying non-metallic pipes, in economically and technically feasible applications, is extremely appealing and solves the challenging issue of corrosion. However, the lack of reliable inspection technologies for composite pipes determines a certain level of reluctance toward this replacement. As a result, the availability of such an inspection technology may not only reduce the number of failures in non-metallic materials, but it would also eliminate the reluctance toward the change, materializing in the immediate savings associated with the reduction in corrosion costs.

There are a variety of failures in non-metallic pipes and vessels; however, none of them resemble the types of failures observed in metallic pipes, mainly due to corrosion. This confirms that all the inspection technologies that maintain the same detection standards used for metallic pipes have the tendency to miss sensitivity and practicability targets. In fact, it is extremely rare to find defects resembling the voids encountered in non-metallic pipes as a consequence of corrosion. Most failures in non-metallic pipes are due to pressure buildup and tensions in the material, which lead to rapid rupture, or due to an intermediate phase of leak under pressure, but no remarkable material discontinuities are observed.

Continuous efforts are being made in developing new non-destructive testing (NDT) technologies for non-metallic pipes; nevertheless, up to now, no available solution has been proven reliable or sensitive enough to be deployed in the field. One of the main reasons for this gap is that all experimental inspection techniques proposed are adaptations of inspection techniques used for metallic materials. While the application of metallic and non-metallic materials in this case is the same (pipes), their nature is rather
different, mainly in terms of conductivity and in terms of the types of defects occurring.\textsuperscript{11}

In this vein, terahertz (THz) radiation can be defined as the region of the electromagnetic spectrum with frequencies between 0.1 THz and 10 THz or with wavelengths between 3 mm and 30 $\mu$m.\textsuperscript{11} The so-called THz “gap” falls between the microwave region and the infrared/optical region. Microwave electronic devices are typically comparable in size to the wavelength of the radiation and support single-mode or low order mode guided waves. In contrast, optical and infrared devices have dimensions much larger than the wavelength and often support beams containing several modes.\textsuperscript{12,13} Thus, THz systems have four particular advantages: (i) THz radiation can penetrate many common barrier materials to detect concealed objects; (ii) the short wavelength provides adequate imaging resolution; (iii) the low photon energy enables nonionizing radiation and nondestructive detection possibilities; and (iv) the characteristic spectra of some materials can be used as an identifying criterion. This has perhaps, fortunately, preserved some unique science and applications for tomorrow’s technology.\textsuperscript{14–23}

The remainder of this paper is organized as follows: We first analyze the possibility of underground detection of spilt water/oil from buried pipes. We then discuss the content determination and sensitivity of THz waves toward that goal. After that, we derive numerical simulations demonstrating that both frequency-domain and time-domain THz signals permit the detection of small cracks in the pipe, before giving some concluding remarks. Appendixes A and B provide an analysis of the possibility of thickness measurement using THz waves as well as the non-metallic pipe materials used in O&G.

II. THz TESTING AND CHARACTERIZATION

A. Detection of buried spilt water

One issue usually encountered in the oil and gas industry is water leakage from below surface buried pipes. This represents an important limitation, as such pipe defects leading to leakage may remain undetected for long periods of time. Therefore, it is necessary to develop a method to measure this phenomenon as typical techniques of leak detection cannot be applied to plastic pipes. For instance, acoustic signals are usually used, but since non-metallic pipes do not transmit well sound waves, this technique is somehow inefficient. Using wireless GHz/THz waves, we propose to detect spilt water under the soil (1 m underground) with various thicknesses of the liquid. First, we run the electromagnetic simulation (see Appendix A) for an air/sand interface [dashed line in Fig. 1(a)] and for a pipe filled with air and with water. Next, we consider the case of spilt water of 5 cm and 10 cm thickness. We also consider two scenarios: a low frequency regime spanning the range 1 GHz–1.35 GHz and a high frequency regime, i.e., 100 GHz–101 GHz, for the calculation of the reflection coefficient. From Fig. 1(a), it can be seen that the lower frequency is better suited to detect the spilt water, by measuring the shift in the frequency of the maxima of the reflection or its bandwidth, as well as the change in its amplitude. For higher frequencies, shown in Fig. 1(b), it is also possible to detect the spilt...
water, but the shift is less pronounced, meaning less sensitive detection of underground spilt water. For wet soils that possess different refractive indices (with higher absorption rates in the GHz/THz region), the detection becomes more difficult in the low frequency regime, as shown in Fig. 1(c), and impractical in the same high frequency regime due to the ultra-high absorption of THz radiation by the water already present in the soil.

B. Content determination

It is well known that nonpolar and non-metallic materials, i.e., dielectrics such as paper, plastic, clothes, wood, and ceramics that are usually opaque at optical wavelengths, are transparent to THz radiation. This means that a plastic pipe would be transparent to the THz incident field. However, because of the high absorption of water in the THz region, hydrated substances may be easily differentiated. We performed numerical simulations using the commercial software Comsol Multiphysics to compute the amount of energy transmitted and reflected when using an incident THz wave of varying frequency on a long plastic pipe made of reinforced thermoplastic (RTP).

Since the pipe considered here was assumed to be extremely long, two-dimensional (2D) simulations were performed. The diameter of the pipe was taken as 10 cm and the thickness of its wall 1 cm. When the pipe is empty, i.e., only air is inside, the transmission of the signal is almost unity, and there is no reflection, neither absorption, due to the transparency of the RTP plastic. When a mixture of water and benzene is present, drastic changes in the absorption spectra can be observed in Fig. 2. In fact, as stated earlier, due to its high interaction with the THz spectrum, water is a very good absorber at these frequencies, and this is confirmed by our numerical simulations. Here, we consider two separate phases of water and benzene (as benzene is lighter, it floats on top of water).

When we have 50% of water present in the pipe, the absorption is relatively high at a frequency close to 0.6 THz, as shown in Fig. 2(a). When the amount of water increases, the absorption increases significantly around the same frequency, as observed in Fig. 2(b), where 75% of water fills the RTP pipe. The inset of Fig. 2(a) shows a map of the electric field at a frequency of 0.6 THz, where a discontinuity exists at the interface between two fluids. These simulations clearly show that the frequency-domain THz waves are very sensitive to the presence of water and/or hydrocarbon inside the plastic pipes. The inset in Fig. 2(b) shows the maximum computed absorption vs the amount of water.

![Fig. 2](image-url)  
**Fig. 2.** Transmission and reflection spectra for a 10 cm diameter pipe when it contains (a) 50% water and 50% benzene and (b) 75% water and 25% benzene. The inset in (a) shows the distribution of the amplitude of the electric field near the maximum of absorption. The inset in (b) gives the maximum of absorption vs the amount of water in the pipe.

![Fig. 3](image-url)  
**Fig. 3.** (a) The electric field norm at a frequency of 4.225 THz. (b) The S-parameters, in a dB scale, as functions of the frequency without (dashed lines) and with (solid lines) crack. The subscript nc stands for the case of no-crack, whereas the subscript c stands for the case of the presence of a crack.
III. DETECTION OF DEFECTS IN NON-METALLIC PIPES

A. Frequency-domain simulations

We make use of THz waves for quality control and detection of defects inside non-metallic pipes. In fact, non-destructive testing of plastic joints and pipes is one of the current major concerns associated with the existing technologies. X rays and ultrasonic waves are not able to satisfactorily identify inclusions or delamination, and the only means of obtaining low failure rates has been the careful monitoring of the welding process parameters during installation.

We performed the following simulation, where we considered a plastic pipe in the form of a H-bend waveguide that is usually used in the O&G industry. We excite it from the top with the THz radiation, and we compute the transmission spectra at the other end. Both ends were modeled with COMSOL using the port boundary conditions. The diameter of the pipe is 10 cm, and its material, as previously, is RTP.

Figure 3(a) shows the norm of the electric field in the cutplane at one of the frequencies where the bend has a resonance. The absence of a wave pattern in the input section indicates that the transmission is nearly perfect. In this structure, we added a small triangular defect in the bend region. Figure 3(b) shows the S-parameters vs frequency for both structures with and without defects. In addition, there is a clear and significant shift in the resonance frequency that can be observed from 5.1 THz to 5.15 THz, highlighted by the red arrow.

From these simulations, it can be observed that a small defect (or bump) sized at close to 1 cm can be detected in a non-destructive manner, using THz radiation, when the pipe is used as the waveguide of the THz signal.

B. Time-domain simulations

Of more importance is the detection of fissures in the pipe structure, when the electromagnetic signal is impinging on the pipe from the outside. In this case, frequency-domain simulations are not efficient in detecting small irregularities on the surface of the pipe as shown in numerical simulations. In order to detect these scatterers, time-domain simulations are required.

The incident THz pulse is given by

\[ E(t) = e^{-2\tau^2} \sin(2\pi\tau) \text{ with } \tau = t/t_0, \]  

(1)

where \( t_0 \) is the width of the Gaussian pulse (taken to be 1 ps to correspond to the THz signals). Figure 4 gives the amplitude of the pulse

![FIG. 4](image) (a) Time-domain pulse when the pipe is perfect (blue dashed line) and when it has a crack of 3 mm (red line) and 5 mm size (black line). [(b) and (c)] A zoomed-in view around a specific time-domain range to indicate the detection points around the maxima or minima of the electric signal.
in the time range of 0 ps–10 ps. Three cases are considered, the blue dashed line shows the pulse when there is no crack, while the red line and black line show a crack of size 3 mm and 5 mm, respectively. As shown in Fig. 4, around several of the minima and maximum values, there is a mismatch between the responses. This difference permits the detection of the crack by means of the terahertz pulse (green and blue boxes in this figure indicate the locations of maximum detection). It should also be added that the relative difference between the bare and cracked pipe’s signals reaches for some time [near 8 ps, as shown in Fig. 4(c)] more than 100%, which is far beyond any noise signal strength.

IV. CONCLUSIONS AND OUTLOOK

To conclude, we have shown in this paper the versatility of THz signals for thickness measurement and crack detection in non-metallic pipes, commonly used in the oil and gas industry for fluid transport. We have also investigated the feasibility of underground detection of spilled water and/or hydrocarbons. Our numerical simulations demonstrate that THz waves cannot penetrate soil for significant distances and, therefore, only lower frequencies such as low GHz or MHz can be used to detect the limited thickness of spilled liquids under the ground such as sand (dry and wet). We have also performed frequency-domain and time-domain simulations to detect cracks in plastic pipes and show that the time-domain simulations are more appropriate to detect small deformations (in the range of millimeters). Thus, this paper demonstrates the feasibility of using THz technology for the inspection of non-metallic assets, answering current demands from inspection engineers in companies capable of deploying non-metallic materials to mitigate costs associated with metallic assets.

APPENDIX A: THICKNESS MEASUREMENT WITH THz

Electromagnetic (EM) waves interact with matter in different ways. It depends on the radiation power, the frequency (terahertz in our case), and the characteristic of the physical medium with which it interacts. As a consequence, electromagnetic waves of different frequencies interact differently with the medium through which they propagate. This interaction may be analyzed in the receiver sensor measuring the parameters that characterize the signal (amplitude, propagation speed, phase, and frequency), as shown in Fig. 5(a). Material is characterized by electromagnetic parameters (permittivity, conductivity, and permeability) as well as its thickness, which can be used to detect it. Different frequencies and different matter parameters induce different interaction mechanisms: the medium can be analyzed, measuring in the receiver after the interaction. In fact, the period of the transmitted signal permits us to determine the product of the refractive index and the thickness of the sample. Measuring the minimum of the transmission also permits us to have the impedance of the medium and thus its permittivity. In this simulation, we make use of THz signals to determine both permittivity and thickness of the layer [see Fig. 5(b)].

APPENDIX B: TERAHERTZ PROPERTIES OF PIPES’ MATERIAL

Non-metallic pipes are made of a plastic material that is not as resistant to pressure and temperature as metallic pipes. However, they are lighter in weight, in some cases spoolable and most importantly resistant to corrosion. Three different plastics are commonly used, which are PVC (polyvinyl chloride), PE (polyethylene), and PP (polypropylene). Their diameters (of pipe) range from 4 in. to 8 in. (i.e., from 10 cm to 20 cm), as shown in Fig. 5(c).

Among the large variety of available polymers, there are some that present excellent terahertz transparencies with a relatively low
reflectivity. The best materials in this sense are TPX (polymethylpentene), high density polyethylene (HDPE), and polytetrafluoroethylene (PTFE or Teflon). At longer wavelengths, the transmission of these polymers is structureless and flat. Going to shorter wavelengths, mainly below 200 μm, the characteristic bands of intrinsic vibrations appear and scattering due to inhomogeneities increases. Polymers generally become increasingly opaque at shorter wavelengths. For instance, a 1 cm thick layer of HDPE permits a 56% transmission at 0.6 THz and only 16% at 1 THz due to higher absorption (high imaginary part of the refractive index).

DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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