Dielectric Properties of Jordanian oil shales

Mohammad Al-Harahsheh¹, Sam Kingman², Abdurrahman Saied², John Robinson² Georgios Dimitrakis², Hani Al-Nawafelah¹

¹Department of Mining Engineering, Faculty of Mining & Environmental Engineering, Al-Hussein Bin Talal University, Ma’an 20, Jordan

²Process and Environmental Research Division, Faculty Engineering, University of Nottingham, Nottingham, NG7 2RD, UK
TALK OUTLINE

• Background
  – What are dielectric properties?
    • Why we need to know dielectric properties?
    • How to measure dielectric properties?
  – What are Microwaves?
  – Microwave Heating Principles

• Experimental work
  – Measurement method and sampling
  – The Rig

• Results
  – TOC vs. $\varepsilon'$ and $\varepsilon''$
  – Effect of Temperature
  – Effect of Frequency
  – Penetration Depth

• Concluding Remarks
What are dielectric properties?

\[ \varepsilon^* = \varepsilon' - j\varepsilon'' \]

**Permittivity**

- Real part (dielectric constant)
  - Ability of the material to store EM energy within its structure

- Imaginary part (loss factor)
  - Ability of the material to dissipate the stored energy into heat
  - \(< 10^{-2} \): low loss type, difficult to heat with microwaves
  - \(> 5\): depth of penetration can be small, non-uniform heating results, heating very rapid
  - Typically increases with temperature, sometimes sharply!
Penetration depth \((D_p)\) determined by dielectric properties & frequency

- Typically cm at 2450 MHz
- Object >> \(D_p\), non-uniform heating

**Loss Tangent:**

- How well a material dissipates stored energy

\[
\tan \delta = \frac{\varepsilon''}{\varepsilon'}
\]

**Power vs. Penetration Depth**

\[
D_p = \frac{c}{2\pi\sqrt{2\varepsilon'}\left[\sqrt{1+\tan^2 \delta} - 1\right]^{1/2}}
\]
Microwave Heating Equation

\[ Pd = 2 \pi f \varepsilon_0 \varepsilon'' E_0^2 \]

Where

- \( Pd \) is power density (W/m\(^3\))
- \( f \) is frequency of applied radiation (Hz)
- \( \varepsilon_0 \) is permittivity of free space (8.854 \times 10^{-12} \text{F/m})
- \( \varepsilon'' \) is effective dielectric loss factor of the material
- \( E_0 \) is magnitude of electric field within material (V/m)

Why we need dielectric properties?

- The microwave heating equation shows how power density is influenced by the properties of the material being heated.
- Dielectric properties are crucial in determining how efficiently a material absorbs microwaves and heats up.

- The permittivity \( \varepsilon_0 \) and dielectric loss factor \( \varepsilon'' \) play key roles in this process, affecting how much energy is transferred to the material.

- Understanding these properties is essential in applications like microwave ovens, where the goal is to heat food uniformly and efficiently.
Why we need dielectric properties?

- Dielectric properties of materials vary greatly, variation occurs as a result of:
  - composition
  - density
  - temperature
  - frequency

- Knowledge is essential for system design
- Published data should only be used as a guide
Microwave Heating Basics

• Conventional heating
  – entire furnace is hot
  – sample hotter on surface (initially)

• Microwave heating
  – only sample is heated
  – heating is volumetric
  – sample ends up hotter in centre
Microwave Interaction with Materials

- Transparent material: Teflon, Quartz glass, Silica
- Absorbing material: oxides, Ionic species, Polar solvents
- Reflecting material: Metals
Microwave Heating Mechanism

Orientation polarization

When microwave energy is passing through the matter, molecules of the matter having dipole moments will rotate and try to align themselves with the electric field.

Polar ends of molecules tend to align themselves and oscillate in step with the oscillating electric field of microwaves. Collisions and friction between the moving molecules result in heating. Generally, the more polar is a molecule, the more effectively it will couple with microwaves.

- http://homepages.ed.ac.uk/ah05/microwave.html
Microwave Heating Mechanism

Conduction mechanism

If the material irradiated is an electrical conductor, the charge carriers are moved through the material under the influence of the electric field. The induced currents will cause heating in the sample due to electrical resistance.

If the material is too conducting microwaves will not penetrate through causing arcing on the surface.

•http://homepages.ed.ac.uk/ah05/microwave.html
Measurement of dielectric properties

- Cavity perturbation method
  - Possibility to measure at high T
  - Based on simple perturbation theory
  - Very small powdered sample
  - Limited number of frequencies
  - Suitable for low loss materials

- Coaxial probe method
  - Broad band technique
  - Can be used with block sample
  - Suitable for high loss materials
  - Polished surface is required
Hot Cavity Perturbation Method

- Experimental Set-up

- tube furnace
- TM$_{0n0}$ Cavity
- Network Analyzer
- PC
- Furnace controller
- Sample holder
- Actuator
Results 1

TOC vs. $\varepsilon''$

@2.47 GHz
Results 2

TOC vs. $\varepsilon''$ & % Moisture

@2.47 GHz

TOC, %

Moisture Content

Loss Factor

$\varepsilon''$, Moisture before drying, %
Results 3
TOC vs. $\varepsilon''$ – Effect of Drying

@2.47 GHz

Loss Factor

$\varepsilon''$

$\varepsilon''$ after drying

TOC, %
Results 4

TOC vs. $\varepsilon'$

Dielectric Constant

$\varepsilon'$ after drying

$\varepsilon'$

@2.47 GHz
Results 5
TOC vs. Dp

Penetration depth, M.

TOC, %
Results 6
Effect of Temperature

![Graph showing the effect of temperature on loss factor and dielectric constant with various TOC values at 2.47 GHz.](image)
Coaxial probe method
Effect of Frequency
As Received & dried

![Graph showing the effect of frequency on dielectric constant and loss factor for as received and dried samples.](image)
Effect of Frequency
As Received 1

TOC = 17.5%
Penetration depth

Frequency, GHz

Penetration depth, M

Dp-As received
Dp-Dry
Conclusions

• Knowledge of dielectric properties is essential to evaluate the whether EM energy is suitable to heat materials or not
• Short description of microwave heating principles was given
• Water content is the major contributor to both imaginary and real parts of oil shale permittivity
• Imaginary part (loss factor) of oil shale drops significantly after drying
• Above 500 °C, oil shale experiences a sharp increase in loss factor leading to thermal runaway. This effect increases with increased TOC
  – The reason for that is the carbonization of oil organic matter
Conclusions

• Loss factor decreases with frequency from about 1.6 @ 100MHz to about 0.2 at 3 GHz
• To make use of microwave energy for pyrolysis of oil shale, water content, particle size, frequency, and incident power are the major controlling factors of the pyrolysis process
Thank you

???