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Near Field Resonant Capacitive Heating of Water

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ABSTRACT

Remediation of water from tailings is a critical and challenging issue in many industries, particularly in oil sand refineries and waste water treatment. Mining of the Canadian oil sands, also one of the largest known crude petroleum reserve in the world, is done to extract bitumen by the processes like hot water extraction, resulting in numerous amounts of tailings (large ponds). Techniques that can achieve contaminant separation over large surface areas/volumes, with low energy input, and at a low economic investment are of primary interest. Hence, such techniques can be applied for the manufacturing industries with the similar concerns. In this paper, a dielectric heating method is presented that combines electrical standing wave voltage amplification with porous interface (carbon foam) materials to intensify water evaporation. The system targets the dielectric loss tangent of the aqueous solution accompanied with porous interface by operating at a high voltage and frequency in the low megahertz (1-5 MHz). The non-uniform charge distributions across the interface material enables distributed heat localization at the air-water/material boundary, therefore avoiding bulk heating. The most important parameters determining efficiency of capacitive heating are determining the resonant frequency of material in contact with the heating end of helix, and properties of the interface material. Different porous configurations treated for the application were applied as interface layers and the experimental results demonstrate an 80% increase in evaporation rates compared to solar and natural heating. The combination of electrical heating with reduced heat losses results in accelerated vapor generation. Hence, results showcase heat localization at the interface, electric field at the heating boundary and energy requirements for the mentioned scenario. The proposed method offers a promising solution to localize heat over a large area by application of low-cost porous materials and high voltage/high frequency electrical resonators for use in water treatment,

remediation, and go further with distillation applications for water reclamation.

Keywords: Near Field RF heating, Heat localization, interface media, Evaporation

NOMENCLATURE

V	Voltage in volts
A	Absorbance
T	Transmittance %
I	light intensity entering
ε	Permittivity
ε''	dielectric loss
ε'	dielectric constant
$tan\delta$	dielectric loss constant
ρ	material density
c_p	specific heat of the material
k	thermal conductivity and
q	heat
I	current in amps
R	resistance in ohms
t	time in seconds
Q	Charge in coulombs
PPI	Pores per Inch
PVC	Polyvinyl Chloride
RF	Radio frequency

1. INTRODUCTION

Oil sands production in Alberta has been expanding rapidly from past decade increasing the concerns of environmental impacts. Surface oil mining is one technique where oil sands are scooped from the land and bitumen is extracted, this process uses innumerous amounts of water leading to increased water usage and re-usability concerns (Jordaan, 2012). These large quantities of toxic waste water comprising of water (65% wt.), sands, slit, clay, and bitumen is produced as by-product of oil extraction. Currently, this filtration of tailings is a very slow process leading to long term storage hence increasing the number of tailings, which is costly to handle and posing serious environmental concerns. Different processes developed for the management of tailing ponds over the years. Main challenges are faced in efficient dewatering and the high energy-intensive pre-process. Therefore, work is required in the area to efficiently tackle this water problem by not adding to the existing number of tailing ponds in the area (EPA; Parks).

Radio frequency (RF) heating or dielectric heating has application in food industry and plethora of research has been done in the area. Di-electric heating involves heating of electrically insulated materials by dielectric loss. Varying magnetic field across the material results in energy dissipation as the molecules continuously change with electric field. This can be done in two ways: 1) far-field, and 2) near-field by heating electrodes (Abraham et al., 2013). Near-field RF heating has various applications designed in bio-medical implants (Ko et al., 1977), powering vehicle, optical microscopy and spectroscopy (Jones & Raschke, 2012; Taubner et al., 2004).

Here we are proposing the near field capacitive heating as a solution to accelerate evaporation from tailing pond in oil refineries or manufacturing industries with the similar concerns. In this paper, laboratory experiments were conducted considering the different concentrations of the di-electric materials and compared with general di-electric heating rates. The purpose of this research is to increase the evaporation of waste toxic water byproduct from facilities like oil refineries facilitating them for less energy treatment methods. In this paper, tap water is utilized for experimental studies with radio wave frequency ranging from 1-5 MHz. Results demonstrate high evaporation rates while taking less energy input when compared with traditional methods. This paper is focused on the rate of evaporation through dielectric heating of tap water by a solenoid with and without a dielectric material (an insulator). When di-electric material is used, an insulator material is placed at surface layers of water. Di-electric heating can also be efficiently used in treating toxic water as proposed in this paper where less energy could be used when compared with currently available methods such as Reverse Osmosis, and Forward Osmosis.

2. MATERIALS AND METHODS

A porous material made with carbon is employed as an air-water interface material, Figure 1.

Figure 1: Porous carbon foam material used as interface medium in experiments

Porosity of carbon foam can be varied. With increase in porosity of carbon, density is decreased as void space is dominated. The carbon foam is chemically processed with a four molar nitric acid solution for four hours under continuous stirring, in order to make it hydrophilic (Kuzhir et al., 2017). The hydrophilicity of the carbon foam helps the greater rate of capillary action, so enhance the liquid delivery for evaporation.

As the carbon foam is a porous medium, the capillary action of the media lets the water vapor to escape from the porous arrangement. The optical properties of this interface material were measured using a GENESYS 10S UV-Vis Spectrophotometer. According to the Beer-Lambert law, absorbance (A) is given as (Swinehart D. F., 1962)

$$A = -log_{10}\frac{I}{I_O} = acX \qquad (1)$$

where A is absorbance, ε is molar absorptivity, I and I_O are intensities of monochromatic light entering through one face of sample and exiting through other face of cuvette, respectively. The relation between transmittance and absorbance in terms of wavelength can be written as:

$$A = -log_{10}T \qquad (2)$$

where T is Transmittance, values experimentally measured for the porous material are seen in Figure 2. Since the transmittance values of the material is less than 15%, it is implied that the conduction losses are minimum to the surrounding material.

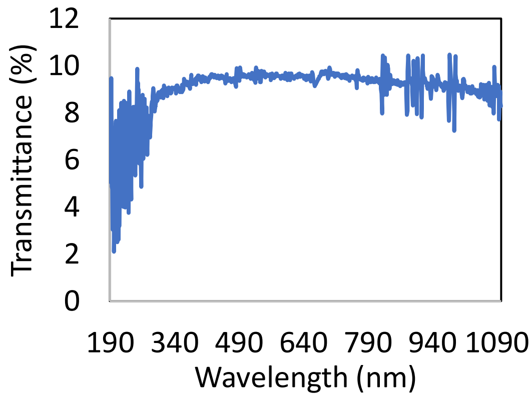
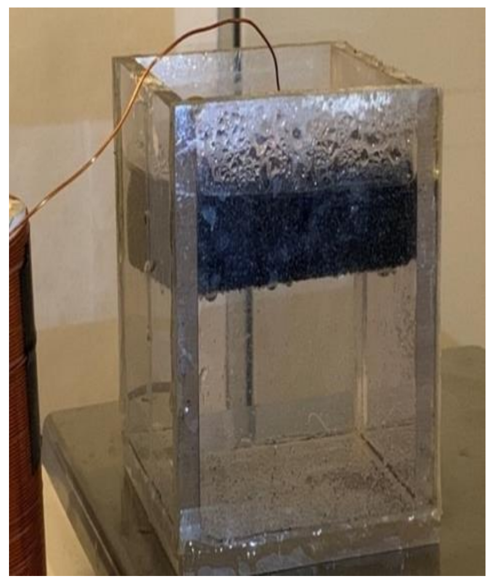


Figure 2: Optical transmittance of Carbon Foam interface medium, measured with GENESYS 10S UV-Vis Spectrophotometer

3. Experimental Setup

The proposed work was done using a function generator, radio frequency amplifier, Oscilloscope, solenoid wound around non-magnetic tube and an acrylic container with water to be evaporated or treated. One end of the copper wound helix acts as input source and other end is categorized as the heating end, and acts as input to the treatment pond/prototype. Equipment and arrangement are shown in Figure 3a. A proposedly di-electric material of porous texture is placed at the air-water interface as shown in Figure 3b, where heating end is placed in the material. Two carbon foam porosities of 20 and 45 pores per inch (PPI) are tested as interface media, each is one inch thick.

(a)



(b)

Figure 3: (a) experimental set-up of radio frequency capacitive heating with RF power amplifier, function generator, Oscilloscope, and (b) acrylic prototype used for test, with the interface/di-electric material placed at the air-water interface.

Temperatures readings at definite time intervals are taken at three depth levels are acquired using J type thermocouples, connected to a Keysight data acquisition unit. Thermocouples are arranged at three different depths to study water temperatures at three locations. When the temperature is measured, test unit was on standby, to maintain electric field undisturbed from thermocouple interaction.

4. Theory

When AC input is given to any dielectric material, molecules align respectively depending on the material (Abraham et al., 2013; Van Neste et al., 2014). Energy dissipation decreases with increase in frequency directly related to dielectric loss. Dielectric heating is majorly material dependent

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (3)$$

Where Permittivity (ε) of the material is given by complex equation of imaginary product of j and dielectric loss (ε'') subtracted from dielectric constant (ε').

Electric power density lost per unit volume in the form of heat is given as:

$$q = \omega\varepsilon'(tan\delta)E^2 \quad (4)$$

Where E is electric field strength and $tan\delta$ is dielectric loss constant, it is expressed as ratio of dielectric losses to the dielectric constant.

$$(tan\delta) = \frac{\sigma + \omega\varepsilon''}{\omega\varepsilon'} \quad (5)$$

To develop temperature profiles while capacitive heating, heat transfer equation in electromagnetic field is expressed in the following terms:

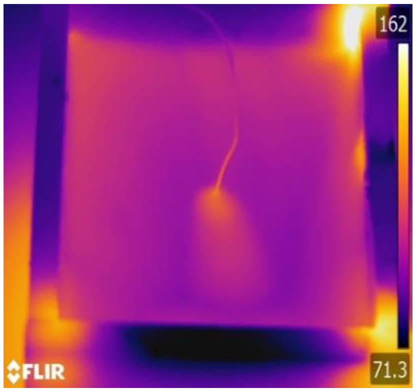
$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\mathrm{k}\nabla T) + q \quad (6)$$

Where ρ is material density, $c_p$is specific heat of the material, k is thermal conductivity and q is heat

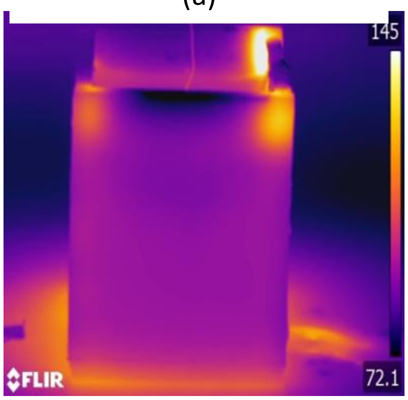
5. Results

When an alternating current is applied at a specific frequency and amplitude in the range of radio frequency. Molecular moment line up with changing electric field, the heating tip of the solenoid is immersed in the dielectric medium or water when testing the baseline case. Energy from the heating end is transferred to the surrounding material in the form of thermal energy. Thereby, heating the water resulting in vapor generation, escaping through the pores of interface media, by the application of capillary action of porous arrangement. When heat is applied to the material and heat localizing abilities of the material are used to localize heat thereby accelerating the evaporation rates. Here dielectric properties of the interface material are considered beneficial for not transmitting heat to the bottom layers, evident from Figure 4. Infrared images are taken at regular intervals from the beginning till end of the experiment.

Figure 5 (a) shows the mass evaporated in 2 tested cases with and without interface heating. A mass balance is placed beneath the prototype to continuous record the mass change data. The higher the frequency is set; the more energy is released. However, this frequency range is set based on the material where this energy is to be imparted. The frequency of material at which the heating starts is termed as resonant frequency of material, where the heating end is in immersed. This can be said from waveform pk-pk voltage from O-scope.



(a)



(b)

Figure 4: Infrared image of prototype at the end of test; (a) top view, and (b) side view.

Energy consumption calculations are done based on Ohm's law, where

$$V = I \times R \tag{7}$$

V is voltage in volts, I is current in amps, R resistance in ohms.

Charge

$$Q = I \times t \tag{8}$$

t is time in seconds. From this energy transferred is calculated

$$E = V \times I \times t \tag{9}$$

Figure 5 shows the energy consumption in base and interface case. In this test scenario, medium was considered as load for power transmission, consequently energy consumption rates varied. Energy consumption is 5.7 times less with carbon foam of 45 PPI dielectric medium, due to effective heat transfer. At 162°F temperature, bubbles formed at the top four corners of the container as in Figure 4, this appeared as an indication of heating and vaporization followed the process.

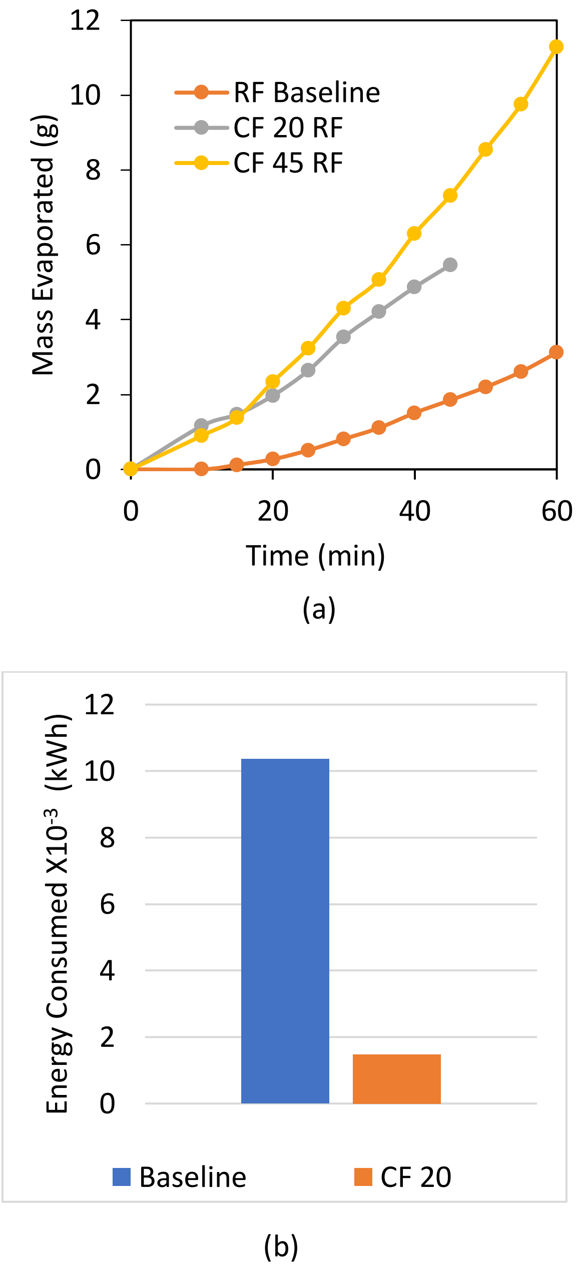


Figure 5: (a) amount of mass evaporated from the prototype (b) amount of energy consumed for evaporating water in each test case

6. Conclusion

Evaporation rates with two different interface materials are studied and energy consumption is calculated using Ohm’s law. Concluding the work, experimental results showed accelerated evaporation rates throughout the experiment and in comparison, with solar based evaporation. Characteristic resonant frequency is varied depending on the material used, and this application is beneficial in reducing the energy consumption. This frequency is recorded for both water or porous interface and this technique is termed as near-field standing wave resonance. With the addition of porous interface, capillary action of the pores aided in mass transfer rates. Therefore, high evaporation rates are recorded and resulted less energy consumption in comparison to baseline.
Baseline RF heating manifested 50% increase in evaporation rates when compared to solar based evaporation (Bahraseman, 2017; Jaladi et al., 2019). For carbon foam 45 PPI, total mass transfer per unit area calculated is 3.05 kg/m^2, which is 81% higher in case of porous interface. At 162°F phase change from water to vapor is occurred, even before the boiling temperature of the water, due to composite interface.

Capacitive RF heating has huge potential in water treatments, rapid heating pattern shows how advantageous is the technique. Our results provide a basis on how the near-field radio waves are used for accelerated water evaporation, and this process can further be extended to water distillation by condensing, collecting, and re-using.

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References

Abraham, T., Gaikwad, R., Hande, A., Phani, A., Afacan, A., & Thundat, T. (2013). *In Situ Heating of Oil Sands Using an Electrical Standing Wave Resonance Excitation Approach*. 1–16.

Bahraseman, H. G. (2017). *HEAT AND MASS TRANSFER IN THERMAL ENERGY SYSTEMS : EVAPORATION AND ENERGY STORAGE APPLICATIONS* [Tennessee Technological University]. https://search.proquest.com/openview/30114feec86489ae0de6b57f61b64503/1?pq-origsite=gscholar&cbl=18750&diss=y

EPA. (n.d.). *Toxic and Priority Pollutants Under the Clean Water Act*. Retrieved November 19, 2020, from https://www.epa.gov/eg/toxic-and-priority-pollutants-under-clean-water-act

Jaladi, D., Languri, E., & Piras, B. (2019, November 11). Sustainable Waste Water Treatment Using Solar Energy by Heat Localization Through Porous Media. *In ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE) (Vol. 8). American Society of Mechanical Engineers (ASME).* https://doi.org/10.1115/IMECE2019-12189

Jones, A. C., & Raschke, M. B. (2012). Thermal infrared near-field spectroscopy. *Nano Letters*, *12*(3), 1475–1481. https://doi.org/10.1021/nl204201g

Jordaan, S. M. (2012). Land and water impacts of oil sands production in Alberta. *Environmental Science and Technology*, *46*(7), 3611–3617. https://doi.org/10.1021/es203682m

Ko, W. H., Liang, S. P., & Fung, C. D. F. (1977). Design of radio-frequency powered coils for implant instruments. *Medical and Biological Engineering and Computing*, *15*(6), 634–640. https://doi.org/10.1007/BF02457921

Kuzhir, P. P., Letellier, M., Bychanok, D. S., Paddubskaya, O. G., Suslyaev, V. I., Korovin, E. Y., Baturkin, S. A., Fierro, V., & Celzard, A. (2017). Electrical Properties of Carbon Foam in the Microwave Range. *Russian Physics Journal*, *59*(10), 1703–1709. https://doi.org/10.1007/s11182-017-0964-3

Parks, A. E. and. (n.d.). *Alberta Environment and Parks*. Retrieved November 19, 2020, from https://www.alberta.ca/about-oil-overview.aspx

Swinehart D. F. (1962). The Beer-Lambert Law. *JournaL of Chemical EducatioN*, *39*, 333–335.

Taubner, T., Keilmann, F., & Hillenbrand, R. (2004). Nanomechanical resonance tuning and phase effects in optical near-field interaction. *Nano Letters*, *4*(9), 1669–1672. https://doi.org/10.1021/nl0491677

Van Neste, C. W., Hawk, J. E., Phani, A., Backs, J. A. J., Hull, R., Abraham, T., Glassford, S. J., Pickering, A. K., &

Thundat, T. (2014). Single-contact transmission for the quasi-wireless delivery of power over large surfaces. *Wireless Power Transfer*, *1*(2), 75–82. https://doi.org/10.1017/wpt.2014.9