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Technology for 21st Century Manufacturing: Electromagnetic & Wave-Based Processing

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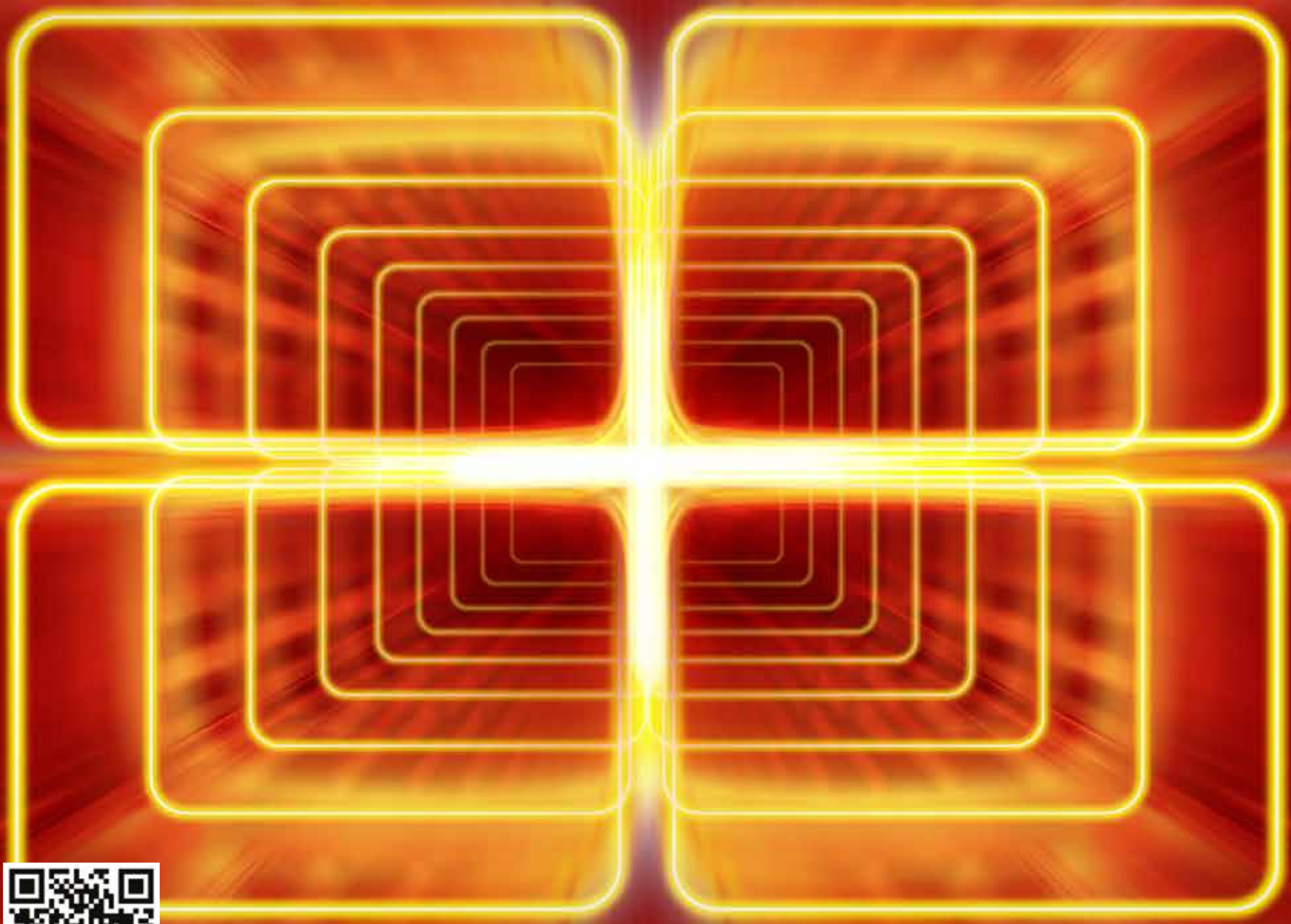

Technology for 21st Century Manufacturing: Electromagnetic & Wave-Based Processing

In this article, Lou Honary, President of WAVEtek Process technology, aims to inspire the reader to consider the potential use of electromagnetic induced manipulation of products for processing lubricants, greases, additives and other related substances, and offers insights into the potential use of a variety of wave-based technologies that can improve the way we treat or prepare lubricants and their derivatives.

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The current method of heating lubricants and related materials has been in use since the late 19th century and throughout the 20th century. While these have been perfected to a most effective state, conventional heating methods are due for reevaluation and are destined for upgrades during this century. The use of electromagnetic waves and their interactions with the molecules of substances go far beyond the simple generation of heat. It extends to targeted manipulation of products' chemistry at their molecular levels, making new or modified products with better properties. While natural magnetism and electrical charges are part of everything we see and feel, including the human body and chemical bonds, our exploitation of their properties is in its infancy. But their growth and utilisation are on an exponential growth trajectory.

The historical development of many disruptive technologies has shown them to be fraught with apprehension, resistance, doubt, and outright obstruction. But safety, ease of use, efficiency and most importantly economics lead to the success of such technologies. The degree to which a disrupting technology is adopted varies and could range from a few years to decades and could be different in different regions of the world. The steam engine, for example, took several decades to become common place in the US. In some cases, disruptive technologies are adopted at lightning speeds; some examples being the internet, cellular telephones, GPS, and electronic trade platforms. In other cases, various bumps in the road slow the progress. In the United States, the use of electric vehicles has become political, causing a slowdown in demand (although many believe that full conversion to EVs is inevitable).

In the August 2019 edition of Lube Magazine[i], this author discussed the potential use of microwaves for processing lubricant products. By detailing the wave-based process and its variation, it is likely that new generations of researchers and product developers will take note and explore their potential. Growth in their usage is a natural progression of technology driven by a desire to develop better products, increase safety, reduce cost or increase efficiency.

[i] *Issue no. 152,* ***https://content.yudu.com/web/1vf9k/0A1vfnf/L152August2019/html/index.html?origin=reader****, Ed.*

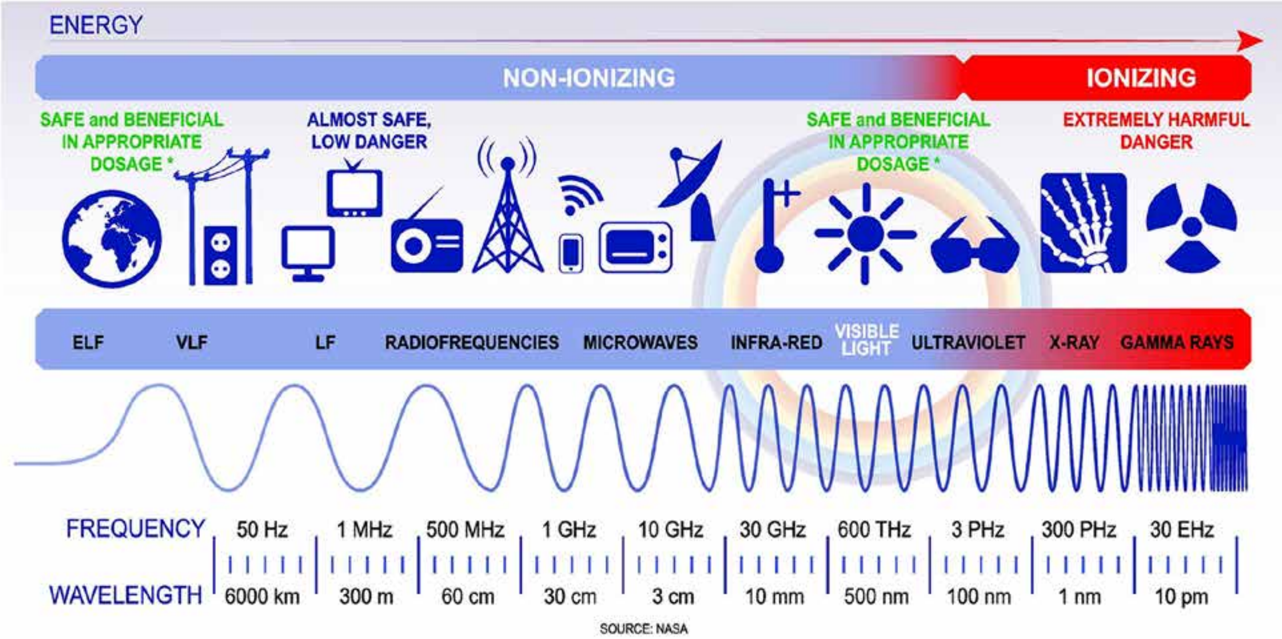

Figure 1: *Electromagnetic Spectrum with Frequency and Wavelengths*[1]

Electromagnetic waves:

The primary natural source of energy waves is the sun, produced from fusion of hydrogen gases, that release intense amounts of energy. It emanates a wide range of waves at frequencies ranging from several kilometers in wave length to micro- and nanometers. The waves radiating from the sun contain the entire electromagnetic spectrum (Figure 1). This means the waves (referred to as sun rays) range in their waviness (frequency) from very large waves like those used in our FM radios with about 300 meters (984 ft and 3 inches) in length, to very small waves like those in x-rays in the range of 1 millionth of a meter (1 nanometer). In Figure 1, the electromagnetic spectrum also shows the range of the waves from 50 Hertz (Hz: full-length wave or one cycle, per second) to 30 EHz (10^{18} Hertz).

It is important to note that some of the waves in the sun's rays are considered relatively safe while others are considered dangerous. On the spectrum, the safer waves are identified as NON-IONISING waves but those considered to be IONISING waves are dangerous. Because most users of microwaves and other wave-based technologies do not know the difference between ionising waves and non-ionising waves, they consider all rays as dangerous (for example, in the US microwaving food is sometime colloquially referred to as "nuking" the food). Such misuse of terms leads to fear of microwaves even when microwave ovens are ubiquitous all around the world and have been in use since the 1950s. Coincidentally, the term nuclear radiation is a good example of dangerous ionising waveforms. Ionising means the radiation has extremely high frequency and can penetrate many barriers. Some radioactive fissile materials carry particles that knock off electrons from atoms of the substance that come into contact with them. The gain or the loss of electrons from an atom results in a negative or a positive ion which is an undesirable change and dangerous to living things. On the other hand, FM and AM (Frequency Modulated and Amplitude Modulated) radio waves, cellular telephones and TV signals, microwaves and some of the visible light coming from the sun have very long wavelengths and cannot penetrate many substances and thus cannot ionise. Hence, they are considered non-ionising and therefore, in general, safe. Nuclear radiation is due to the decaying of atoms of radioactive materials known to be harmful to living organisms. So are x-rays, gamma rays, and beta rays.

On the electromagnetic spectrum it is shown that microwaves have frequencies and wavelengths below even the Ultra Violet (UV) rays which are part of the sunlight. Sunlight's UV rays cause sunburn on skin if sunblock is not used. Ionising waves like x-rays have very high frequencies, so they can penetrate skin tissues and are ionising. Other than using them in short bursts for X-ray imaging, for example, long term unprotected exposure to x-rays is dangerous.

Non-Ionising rays, on the other hand, are everywhere around us including large amounts emitted from the overhead power lines. The degree that humans are adapting to increasing levels of non-ionising waves or the long-term effects of our daily exposures to safe[er] electromagnetic waves may not be known for decades or centuries. The goal at the present is to be aware of the presence of safe, non-ionising waves around us, design devices with protective barriers, and reduce unprotected exposure. This means we should use various available shielding like sunglasses for the eyes, sun blocks for skin, and in the case of x-rays for medical procedures, using lead-based vests for protection. Microwave frequencies are lower in wavelength than infrared and even lower than the visible light. While exposure to sunlight is considered safe, unprotected long-term exposure to sunlight could be hazardous. The same is true for microwaves. Home microwaves have a variety of protective designs that block (choke) microwaves from exiting the cooking chamber. There are also many inexpensive leak detectors that can be used to determine the amount of wave leakage through the protective barriers. Even human bodies emit electromagnetic waves. In human bodies, the main frequency of emission is the result of the body temperature and shifts as the temperature changes. At room temperature it is mostly in the infrared region of the EM spectrum (30-450 THz)[2].

In summary, microwaves can be as safe or as dangerous as sunlight is. With more education and awareness, wave-based technologies are bound to find useability in more applications.

Microwaves and interaction with lubricants

To better appreciate the benefits of using electromagnetic waves for heating, it is important to describe the differences between *direct heating* and *indirect heating*. The current method of heating a liquid, for example, is to apply the heat to a [usually] metal container that contains the liquids so the heated metal object would heat the liquid. This is akin to putting a cup of milk in a pot and heating it on a stove. Electricity heats the heating elements that heat the bottom of the pot which in turn heats the milk exposed to the pot. The main problem with this method of indirect heating is that it creates hot spots (in this case at the bottom of the cooking pot). Hot spots can burn the layer of the product exposed to it, thus stirring and scraping become necessary.

Direct heating on the other hand relies on the interactions of the electric and magnetic fields of electromagnetic waves and the field and charge properties of the product that is being heated. A common household microwave works by passing microwaves usually at a frequency of 2.45 gigahertz (GHz) – (or 2450 million cycles per second) and a wavelength of 122 mm (4.80 inches) through the substance being heated. This means that the magnetic polarity of the wave changes from north to south and vice vera 2450 million times in one second. Additionally, there is an electric field that accompanies the waves (90 degrees apart) that change polarity (or charge from positive to negative and vice versa) 2450 million times per second. For simplicity, one can visualise that the magnetic poles of the product molecules trying to align themselves with the magnetic fields of the incoming waves. At such a high frequency, the molecules of the product impact each other through violent vibration and cause frictional heat the same way when fire under a hot metal generates frictional heat in anything that is in contact with the hot metal. An example of direct heating, on the other hand, would be placing a cup of milk in a microwave for 1-2 minutes and observing that the milk is directly heated through such molecular excitation and is hot, but the cup handle would be cool enough to grab and remove. Direct heating heats the product directly; and indirect heating heats the vessel that contains the product.

In the direct heating of products, due to removal of hot spots, there is no need for scrape agitation or jackets in cooling vessels. The removal of jackets and elimination of gearbox and drives for the side scrapers will reduce the capital equipment cost. The milk heated on the stove will burn if the hotspot is not scraped continuously and the product stirred. The removal of hotspots and the direct excitation of product molecules to generate frictional heat make this method of heating the logical choice for process heating. One of the chief barriers to widespread use includes a lack of understanding of the waves within the electromagnetic spectrum, the nature of microwaves, and a general fear of the unknown.

WAVEGUIDES

Waveguides are an important part of electromagnetic wave transmission! Understanding how they work, and their features, is important in applying wave-based technology to solving problems

***Figure 2:** (a) WR 340 Waveguide to Coaxial Converter and two Coaxial Cable Ends (b) and (c) and a WR 975 Coaxial to Waveguide Converter*

or finding new ways of processing. Although household microwaves have been in use since the 1950s, in general, users are not aware of the fact that microwaves are sent to the cubical cooking chamber via a waveguide. A waveguide is a metal duct specifically designed for waves of different wavelengths. It is important to understand how waves are transmitted in waveguides, because it will underscore its efficacy and flexibility when compared to conventional steam or heat transfer media. Waveguides come in many sizes and shapes, but the most common shape is rectangular. In home microwaves, the waveguide is covered by a plate on one side of the cooking chamber. Waves can travel long distances in waveguides like the ductwork in home heating systems but without losing their wave intensity. Lower power microwaves can also travel in coaxial cables, the same way television signals are sent to the back of older televisions. Microwaves can travel part in waveguide and then switch to travel through coaxial cables and vice versa. Figure 2.

In the case of radars and television signals, waves are also transmitted through the atmosphere and are then collected via horned waveguides or dishes. This means, in using microwaves, the user has the flexibility of sending them through different means be it coaxial cable, airways, or waveguides to be applied to an object. Within our lubricants industry, there are many processes in laboratory or in production that can benefit from electromagnetic waves generated at different frequencies.

For heating purposes, the most common waveguides are Rectangular and are referred to as Waveguide Rectangular (WR) followed by a number. For example, WR 340 is used in home microwaves and WR 975 is used in industrial microwaves. The WR 340 works with frequencies at 2.45 Giga Hertz (GHZ) or 2450 Mega Hertz (MHZ); and industrial microwave WR 975 works with 915 MHZ frequency. Table 1 shows dimensions of different waveguides with highlighted dimensions for WR 340 and WR 975.

Standard sizes of rectangular waveguide								
Waveguide name			Frequency band name	Recommended frequency band of operation (GHz)	Cutoff frequency (GHz) of		Inner dimensions of waveguide opening	
EIA	RCSC *	IEC			lowest order mode	next mode	(inch)	(mm)
WR2300	WG0.0	R3		0.32 — 0.45	0.257	0.513	23.000 × 11.500	584.20 × 292.10
WR2100	WG0	R4		0.35 — 0.50	0.281	0.562	21.000 × 10.500	533.40 × 266.7
WR1800	WG1	R5		0.45 — 0.63	0.328	0.656	18.000 × 9.000	457.20 × 228.6
WR1500	WG2	R6		0.50 — 0.75	0.393	0.787	15.000 × 7.500	381.00 × 190.5
WR1150	WG3	R8		0.63 — 0.97	0.513	1.026	11.500 × 5.750	292.10 × 146.5
WR975	WG4	R9		0.75 — 1.15	0.605	1.211	9.750 × 4.875	247.7 × 123.8
WR770	WG5	R12		0.97 — 1.45	0.766	1.533	7.700 × 3.850	195,6 × 97.79
WR650	WG6	R14	L band (part)	1.15 — 1.72	0.908	1.816	6.500 × 3.250	165.1 × 82.55
WR510	WG7	R18		1.45 — 2.20	1.157	2.314	5.100 × 2.550	129.5 × 64.77
WR430	WG8	R22		1.72 — 2.60	1.372	2.745	4.300 × 2.150	109.2 × 54.61
WR340	WG9A	R26	S band (part)	2.20 — 3.30	1.736	3.471	3.400 × 1.700	86.36 × 43.18
WR284	WG10	R32	S band (part)	2.60 — 3.95	2.078	4.156	2.840 × 1.340 †	72.14 × 34.94

***Table 1:** Waveguide dimensions: Recommended different frequencies*[3]

Waveguides are made with non-ferromagnetic materials like stainless steel, aluminum, copper and the like. They can be solid, but flexible waveguides are also available (Figure 4).

***Figure 3:** Waveguides in different configurations including flexible version*[4]

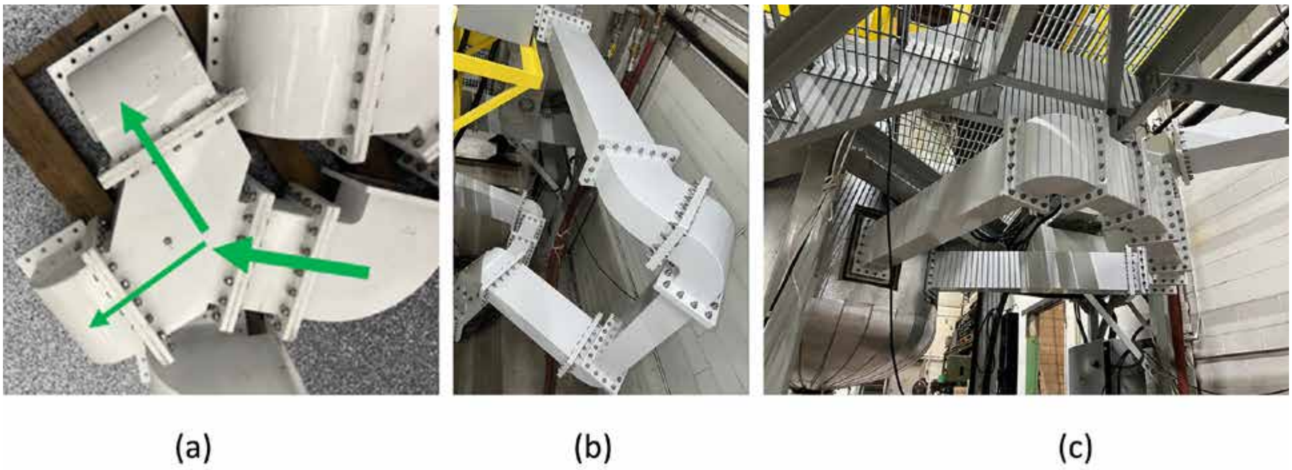

Figure 4: *Examples of Wave Divider (a) Uninstalled and Installed (b) and (C) on a Grease Kettle[5]*

Waveguides can be designed and manipulated to deliver the waves to specific points of use for a variety of applications. For example, we can split the microwave power in two separate waves to be applied to two different sides of a vessel. Figure 4 shows a Patterson kettle that splits 75KW of microwave power into two waveguides each carrying 32.5KW of power to the vessel.

The division of power does not need to be equal and if desired, with a change in the divider, a smaller portion of the power can be sent to one leg of the splitter and the balance to the second leg. Several waveguides can also be combined into one waveguide to deliver combined waves from different sources into one application point. Figure 5 shows microwave combiners. Either several coaxial lines can be combined, or waveguides can be combined.

Figure 5: *Power Combiners merge two or more signals into one[6]*

Through such flexible modes of transmission, using either waveguides or coaxial cables, a variety of manipulation at the molecular level of chemicals can be accomplished. This can be especially exciting for use in laboratory settings when small volumes of products are processed for experimental purposes.

Figure 6 (a) shows a microwave "mantle" type heater which receives the waves through a coaxial cable using product in a test tube to heat with microwaves. A waveguide version of the same microwave (b) can be used for running a pump to circulate the product through the microwave application chamber.

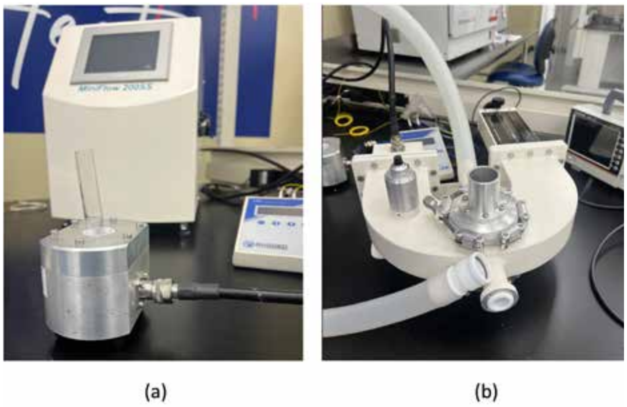

Figure 6: *A microwave "mantle" type heater (a) and a waveguide version of the same (b)*

Another example would be the removal of by-product water from esterification of vegetable oils. Microwaves can directly excite the water molecules and evaporate them out of the ester at precise temperatures more efficiently than heat through jacketed vessels can. A step further, plasmas induced via microwaves can be used for polymerising oils with less damage due to oxidation stability that happens through blowing (heat and oxygen).

Plasma

Microwaves can be used for generating plasmas by activating most hydrocarbon feed and associated molecular hydrogen. Typically microwaves at 2450 MHZ are used to excite electrons, that in turn produce ions through collision with gas atoms and molecules. There are different types of plasma technologies.

Figure 7: *Ann ECR coaxial microwave plasma source that can be used in arrays for application to larger surfaces*[8]

One company has been producing "Aura-Wave ECR plasma source," described as an electronic cyclotron resonance (ECR) microwave coaxial plasma source which can sustain stable plasmas from 10^{-4} to 10^{-2} mbar (0.1 Pa to 10 Pa). Permanent cylindrical magnets are encapsulated and mounted in opposition inside the coaxial structure, allowing the generation of a magnetic field towards the plasma chamber in order to limit losses to the walls."[7] The source makes it possible to reach plasma densities of 10^{11} cm^{-3} in multi-source configuration with a 10 cm working distance, for most gases.

Plasma has been used for modifying oil viscosities through localised polymerisation. The process was used for increasing the viscosity of both mineral and biobased oils. A recent edition of Lube Digital[ii] highlighted the work of the Belgian company Elektrion, that throughout the 20th century had produced viscosity modifiers using this method.

Lasers

Lasers are produced by manipulating the electromagnetic waves into a focused single beam of different intensity and size. The use of lasers in manipulating the properties of oils and additives is yet to be fully explored. According to the US National Ignition Facility (NIF) "A laser is created when electrons in the atoms in optical materials like glass, crystal, or gas absorb the energy from an electrical current or a light. That extra energy "excites" the electrons enough to move from a lower-energy orbit to a higher-energy orbit around the atom's nucleus.

A laser takes advantage of the quantum properties of atoms that absorb, and radiate, particles of light called photons. When electrons in atoms return to their normal orbit—or "ground" state—either spontaneously or when "stimulated" with a light, other energy source, or even another laser in some cases, they emit more photons[9]." Lasers are available in many sizes and shapes and produce either bursts of light or continuous beams. Pulsed lasers could be as short as one billionth of a second. They can be made visible or can be invisible. The ability to focus lasers with varying power levels makes them suitable for numerous applications from cutting, cleaning and welding of metals to etching and circuit board manufacturing.

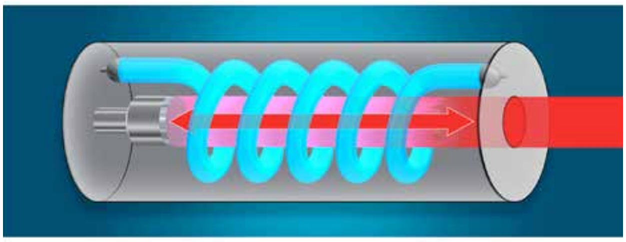

Figure 8: *Light Amplification by Simulated Emission of Radiation (Laser)*[10]

Susceptors

Where products cannot be directly impacted with electromagnetic waves, susceptors can be used as catalysts. In general, susceptors are substances that when exposed to electromagnetic waves produce heat and emit infrared radiation. The best-known use of susceptors is the packaging used in microwave popcorn. Since the corn kernels are devoid of moisture and are solid, they don't respond to common microwaves effectively. So, a grid of thin susceptor film placed in the packing converts the microwaves to radiant heat that in turn pops the corn kernels. Susceptors come in numerous materials and shapes. Some glass substances, especially when containing certain metals, can function as susceptors. It is, therefore, feasible for glass lined vessels to be coated such that the lining would act as a susceptor for heating with microwave materials that are not

[ii] *March 2024,* ***https://www.lube-media.com/wp-content/uploads/DE02-Plasma-Treatment-History-WEB-ONLY-Article-Mar24e.pdf****, Ed.*

microwavable. A good example of a susceptor is silicon carbide which was patented by this author to be used as coating for grease kettles so that mineral oil-based greases could be made using microwaves. One manufacturer has already announced availability of microwave-operated grease kettles that can be used for making petroleum-based greases.

Figure 9: Susceptors placed in a microwavable popcorn bag converts microwaves to infrared in order to pop the corn kernels

Smart fluids

The use of nanoparticles as property enhancers in lubricants has been gaining momentum and their use is expected to continue to grow. The interactions of nanoparticles with electromagnetic waves of varied frequencies have the potential for more focused manipulation of the structure of lubricant molecules. The use of magnetorheological fluids in hydraulic systems has been explored. By applying electromagnetic energy to a flowing fluid containing ferromagnetic particles, one can slow down the flow rate to zero, in effect acting as a flow control valve. Such fluids have also been used in shock absorbers where adjusting the amount of electromagnetic intensity would increase or decrease the rigidity of the shock absorber, such as in driver seats of trucks or in shock absorbers of offroad machinery.

Generation of electromagnetic waves:

In conventional microwaves, waves are generated by a magnetron (formed from the terms magnetic and electron). Developed to enhance the radar technology used during WWII, the magnetron was invented to produce higher frequency radars for faster detection of aerial objects. It relies on the oscillation of electric charges around cavities (cavity electron) which leads to the generation of electromagnetic waves at high frequency. Figure 11 shows a picture of a household magnetron and illustrations of a cavity magnetron with eight cavities. There are several animated educational videos that illustrate the operation of magnetrons on YouTube with their links appearing in the reference section.

Simply explained, a transformer steps up the conventional electrical voltage to very high voltages that can be as high 17,500 volts for the industrial microwaves. The high voltage is then applied to a cathode element resulting in thermionic emission of electrons. This is the same type of emission of electrons in a light bulb when turned on. The clouds of electrons from the cathode are then redirected by two large permanent magnets into a resonance generating cavity. Each cavity creates its own

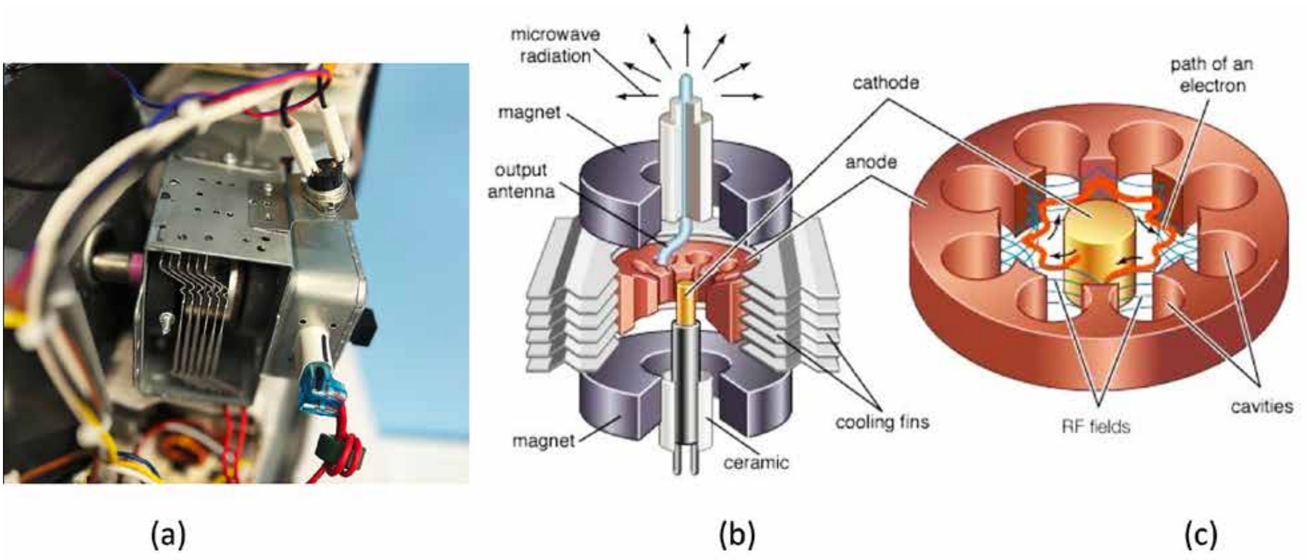

Figure 10: Cavity Magnetron. (a) Magnetron in Home Microwave (b and c) Cavity Magnetron[11]

resonance frequency, so different magnetrons can produce different frequencies. The resonance of electrons in the cavity magnetron results in waves emitting from the magneton which are directed through a circulator into the waveguides.

Figure 11: *Industrial Magnetron (915MHZ) as Installed within the Transmitter*[12]

Figure 12: *A 75 KW Microwave Transmitter with 5ft x 4ft Footprint Showing Magnetron, Circulator and Waveguide opening on the outside*[13]

The genius of the magnetron is in its circular shape that creates a non-contacting on-off resonance at 2450 MHZ in the case of household microwaves. A crude analogy could be the distributor and coil in the creation of sparks in the spark plugs of older internal combustion engines. The on-off switching of the direct current electricity is accomplished by the points in the distributor. Points when closed allow the direct current from a 12V battery to flow into the primary windings of the coil; and interrupt the current when they open. The magnetic fields around the primary grow outward when points are closed, and collapse when the points are open. The induced magnetic field from the primary induces a high voltage in the secondary proportional to the ratio of the windings of the secondary to the primary. So, if the primary has 10 loops of winding and the secondary has 20,000 loops of winding, the induced voltage in the secondary winding would be 2000 times higher (24,000 volts but at proportionally smaller current) of the coil. 24,000 volts is high enough for electrons to jump as a spark across the spark plug gap. In the magnetron the resonance is due to the shape of the magnetron cavity that incorporate the inductive – capacitive circuitry via the cavities. So, there are no points to open and close, rather the switching takes places at the speed of light and is adjusted based on the number of cavities to achieve different frequencies.

By applying high voltages to the cathode in the magnetrons to release electrons, the cathode eventually gets used and loses its ability to effectively release electrons. This is somewhat like an incandescent lightbulb that, after several thousand hours of use, the bulb element becomes tired and gets dimmer or breaks. Magnetrons have an effective use life that depends on the frequency and intensity of their use. Magnetons in industrial microwaves, based on the intensity of their use, can last 3000-6000 hours. Magnetrons in household microwaves can last several years because they are used relatively intermittently.

Newer solid-state microwaves are available that do not use magnetron and instead the waves are generated via solid state circuitry. While the prices of solid-state microwaves are rather prohibitively high, their life expectancy is in the range of 50,000 to 100,000 hours. Solid-state microwave transmitters can allow modulation of the wave frequency within a reasonably wide range making them more suitable for industrial applications. Presently, magnetron-based microwave generators are readily available and economical for many of the intended uses in process industry.

Summary

In this article I have emphasised the benefits of exploring the potential use of natural magnetism and its artificially produced electromagnetism in processing products. In the case of heating for lubricants blending or for reaction in grease or polymer processing, the use of thermal fluids and jacketed vessels are being challenged by safer, more efficient, and economical microwaves. But, beyond heating, the wave-based processes offer opportunities for more focused and targeted manipulation of products at their molecular levels. Plasmas, lasers, sonics, and radars among many others work on the basis of the same principles and should be explored. Many of the conventional processes used in preparation of lubricants and additives present opportunity for improvements with the aid of wave-based technologies. Solid state microwaves that are commercially available allow modulation of microwave frequency to match the specific frequency of the target product's molecules. This means we should be able to apply electromagnetic waves to a mixture of products but excite only some selected molecules within that mixture. The introduction of nanoparticles and smart fluids and the like will further enhance the benefits of using wave-based technologies.

1. Source: US National Aeronautics and Space Administration (NASA) available online.
2. (Source: Emission from human skin in the sub THz frequency band | Scientific Reports (nature.com)).
3. Source Wikipedia, downloaded June 6, 2024 https://en.wikipedia.org/wiki/Waveguide_(radio_frequency)#:~:text=The%20waveguide%20name%20WR%20stands,nearest%20hundredth%20of%20an%20inch.
4. Source: WAVEtek Process Technology, LLC for rigid waveguides and for flexible waveguide: https://www.ebay.com/itm/204721260706?chn=ps&_trkparms=ispr%3D1&amdata=enc%3A1F_iHQMGcTWKN1TRhuuBetQ88&norover=1&mkevt=1&mkrid=711-213727-13078-0&mkcid=2&itemid=204721260706&targetid=4581115214222019&device=c&mktype=&googleloc=&poi=&campaignid=604202288&mkgroupid=1240250168853486&rlsatarget=pla-4581115214222019&abcId=9427717&merchantid=51291&msclkid=01224d8a273419deae662bfa46e56c62
5. Patterson Industries a Division of All-Weld: https://www.pattersonindustries.com/
6. Microwave Techniques: https://www.microwavetechniques.com/
7. Sairem: https://www.sairem.com/solutions-for-microwave-plasma-generation/ecr-microwave-plasma-sources/
8. Ibid
9. https://lasers.llnl.gov/
10. Source: (Lawrance Livermore Laboratories). https://lasers.llnl.gov/education/how-lasers-work
11. Source for (b and c) https://www.researchgate.net/
12. WAVEtek Process Technology, LLC: www.wavetekprocess.com
13. Ibid

Links to YouTube Videos for:

A. Magnetron:
   a. https://www.youtube.com/watch?v=bUsS5KUMLvw&t=220s
   b. https://www.youtube.com/watch?v=ka_SYaDe16k
   c. https://www.youtube.com/watch?v=lQnAadKn1Es&t=32s

B. LC Circuit:
   a. https://www.youtube.com/watch?v=2_y_3_3V-so
   b. https://www.youtube.com/watch?v=Mq-PF1vo9QA
   c. https://www.youtube.com/watch?v=lWyn_eV-DzM

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