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Microwave heating applications in environmental engineering— a review

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Abstract

In this work, microwave heating applications in environmental engineering are reviewed. A number of topics are evaluated, including waste processing, minerals processing, activated carbon regeneration, and remediation of polluted soil. Findings are presented that list the possible commercial development areas as mineral ore grinding, waste sludge processing, volatile organic compound (VOC) treatment and recovery, contaminated soil vitrification, and carbon in pulp gold recovery. There are numerous explanations for why microwave heating technology has not been invested in or implemented in other fields. These include challenges related to scaling up laboratory units to industrial capacity and a dearth of basic information on the dielectric characteristics of materials. Because of this, the development of microwave heating techniques for use in environmental engineering has been delayed. In fact, commercialization is only considered feasible when microwave heating provides further process-specific benefits above traditional heating methods.

1. Introduction

Since World War II, there have been major developments in the use of microwaves for heating applications. After this time it was realised that microwaves had the potential to provide rapid, energy-efficient heating of materials. The main applications of microwave heating today include food processing, wood drying, plastic and rubber treating as well as curing and preheating of ceramics. Broadly speaking, microwave radiation is the term associated with any electromagnetic radiation in the microwave frequency range of 300 MHz– 300 GHz. Domestic and industrial microwave ovens generally operate at a frequency of 2.45 GHz corresponding to a wavelength of 12.2 cm and energy of 1.02×10^{-5} eV (Jacob et al., 1995). However, not all materials can be heated rapidly by microwaves. Materials may be classified into three groups, i.e.conductors, insulators and absorbers (Church, 1993). This classification is illustrated in Fig. 1. Materials that absorb microwave radiation are called dielectrics, thus, microwave heating is also referred to as dielectric heating. Dielectrics have two important properties (Oespchuck, 1984).

- They have very few free charge carriers. When an external electrical field is applied there is very little charge carried through the material matrix.
- The molecules or atoms comprising the dielectric exhibit a dipole movement. A dipole is essentially two equal and opposite charges separated by a finite distance. An example of this is the stereochemistry of covalent bonds in a water molecule, giving the water molecule a dipole movement. Water is the typical case of

a non-symmetric molecule. Dipoles may be a natural feature of the dielectric or they may be induced (Kelly and Rowson, 1995). Distortion of the electron cloud around non-polar molecules or atoms through the presence of an external electric field can induce a temporary dipole movement. This movement generates friction inside the dielectric and the energy is dissipated subsequently as heat.

The interaction of dielectric materials with electromagnetic radiation in the microwave range results in energy absorbance. The ability of a material to absorb energy while in a microwave cavity is related to the loss tangent of the material.

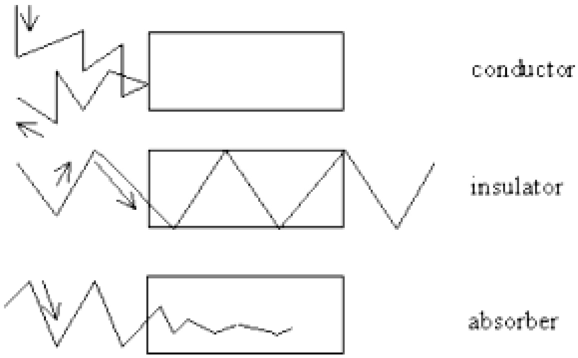

Fig. 1. Microwave absorption characteristics for conductor, insulator and absorber.

This depends on the relaxation times of the molecules in the material, which, in turn, depends on the nature of the functional groups and the volume of the molecule (Gabriel et al., 1998). Generally, the dielectric properties of a material are related to temperature, moisture content, density and material geometry (Metaxas and Meredith, 1993).

An important characteristic of microwave heating is the phenomenon of ‘hotspot’ formation, whereby regions of very high temperature form due to non-uniform heating (Hill and Marchant, 1996). This thermal instability arises because of the non-linear dependence of the electromagnetic and thermal properties of the mate- rial on temperature (Reimbert et al., 1996). The formation of standing waves within the microwave cavity results in some regions being exposed to higher energy than others. This results in an increased rate of heating in these higher energy areas due to the non-linear dependence. Cavity design is an important factor in the control, or the utilisation of this hotspot phenomenon.

Microwave energy is extremely efficient in the selective heating of materials as no energy is wasted in ‘bulk heating’ the sample. This is a clear advantage that microwave heating has over conventional methods (bulk heating in furnaces).

Microwave heating processes are currently undergoing investigation for applica- tion in a number of fields where the advantages of microwave energy may lead to significant savings in energy consumption, process time and environmental remediation.

Compared with conventional heating techniques, microwave heating has the following additional advantages (Ontario Hydro Technologies website, 2001).

S Higher heating rates;
S no direct contact between the heating source and the heated material;
S selective heating may be achieved;
S greater control of the heating or drying process;

S reduced equipment size and waste.

The principal areas of study reviewed in this paper are minerals processing, waste treatment, contaminated soil remediation, recycling of rubber tyres, activated carbon applications and the treatment of volatile organic compounds (VOCs).

Contaminated soil remediation

Electrical heating along with radio frequency (RF) heating was used in the 1970s for the recovery of bitumen from tar sand deposits (Kawala and Atamanczuk, 1998). Low frequency radiation (i.e. RF) has also been used to enhance soil vapour extraction (SVE) of contaminated soils (USEPA, 1995).

Microwave-assisted soil remediation applies to the in situ remediation of sites contaminated with volatile compounds (e.g. polycyclic aromatic hydrocarbons (PAH)s, polychlorinated biphenols (PCBs), etc.) as well as non-volatiles (e.g. heavy metals). In the latter, decontamination follows the vitrification process where glass and other materials are placed on top of the contaminated soil. The soil is then heated by electrical current from electrodes that have been installed deep in the ground of the contaminated site (LaGrega et al., 1994). The glass and soil melt in an amorphous mass, immobilising the contaminants. Glass can be substituted with granular activated carbon while iron wires can ensure deeper penetration of the microwave energy (Tai and Jou, 1998).

Microwave radiation has also been applied to the removal of volatile and semi-volatile components, however, it is especially effective in the case of polar compounds (Kawala and Atamanczuk, 1998). In the case of non-polar compounds, addition of magnetic nanoparticles ensures an increase in the microwave absorption characteristics of the contaminant (Holzwarth et al., 1998). All vapours (including soil moisture) are removed from the soil after the application. Further work found that microwaves could be used to enhance solvent extraction of the contaminants from the soil but the properties of the soil greatly affected the extent to which the contaminants were removed (Punt et al., 1999). For example, high electrical losses are recorded in iron ores (hematite and magnetite) and soils with small salt contents. Microwave energy should, therefore, be deposited when all water has been removed from the soil (Edelstein et al., 1994).

Care should be taken to prevent very high temperatures occurring as carbonisation of humic substances in organic matter-rich soils might occur (Kawala and Atamanczuk, 1998). A temperature of 100 °C was found to be ideal. In addition, 'hotspot' formation could seriously affect any attempt to apply the technology in soil remediation problems. However, successfully taking advantage of this effect would mean that hotspots would form at points in the plume where contaminants are concentrated, without having to heat the entire mass of affected soil to high temperatures. Thus, energy would be saved and the other implications of temperature rise would be avoided.

2. Waste

Microwave heating possess many potential advantages in the treatment of a vast array of wastes. The important characteristics are as summarised below (Rocky Flats Technology Summary, 2001).

S Significant waste volume reduction;
S rapid heating;
S high temperature capabilities;
S selective heating;

S enhanced chemical reactivity;
S ability to treat wastes in situ;
S treatment or immobilisation of hazardous components to meet regulatory requirements for storage, transportation or disposal;
S rapid and flexible process that can also be made remote;
S ease of control;
S process equipment availability, compactness, cost, maintainability;
S portablity of equipment and process;

S improved safety, including reductions in personnel exposure of potentially hazardous chemicals or materials for processing and disposition;
S energy savings;
S cleaner energy source compared with some more conventional systems;
S overall cost effectiveness/savings.

Microwaves are being investigated as a possible treatment for many mixed wastes including process sludges, incinerator ash, and miscellaneous wastes. Due to the restrictions on landfilling it is preferable to reduce the volume of waste being produced. Volumetric reduction is usually achieved through pyrolysis as opposed to incineration to prevent the formation of dioxins, furans and NO_x. Off-gases from the process are sent for further treatment, whilst the residue is usually an inert ash. However, if this remaining material is not inert then further immobilisation techniques may be employed. The contaminants may be vitrified within the remaining waste, with the use of glass (network) formers.

There are many applications for processing PCBs, and associated wastes as many millions of circuit boards must be disposed of each year. A particular problem is the contamination of groundwater if the wastes are landfilled; this is due to the variety of metals in the manufacture of these circuits. In addition, many precious metals are contained within the PCBs. It is desirable to reduce the volume of this waste, immobilise the hazardous components into leach resistant forms and also reclaim and re-use potentially valuable products. This could provide a return on investment, as well as being an environmentally sound strategy. A process of separating the metals contained within these circuits from the plastic (organic) components has been patented (Wicks and Schulz, 2001). It is essentially a two-stage process utilising microwaves to heat the waste to a temperature sufficient to combust the organic materials present. Low melting point metals such as tin and aluminium can be removed after this stage. The second stage involves heating the waste to a higher temperature at which glass formers present in the waste begin to vitrify. Metals with higher melting points can be separated from the solidified waste product or they may be removed at their respective melting points.

A promising application is the processing of wastewater generated from the manufacture of the printed circuit boards. A particular study involved the processing of sediment sludge obtained from a high quality PCB manufacturer in Northern Ireland (Gan, 2000). The process demands that the boards are washed after each individual process to avoid any cross-contamination. Consequently, a large quantity of wash water is required. Almost ninety-five percent of the metal ions are removed subsequently by means of flocculation, pH adjustment and alkaline precipitation processes. The resulting sludge is landfilled, and there is great potential for groundwater contamination. The microwave treatment involves the immobilisation of the metal ions in the sludge. Volume reduction by evaporation of moisture is an important fringe benefit of this method and is shown to be particularly efficient when combined with standard convection drying. This is shown in Fig. 2.

Microwaves are applicable in many sludge treatment processes. The Electric Power Research Institute Centre for Materials Production (EPRI CMP, 2001) state

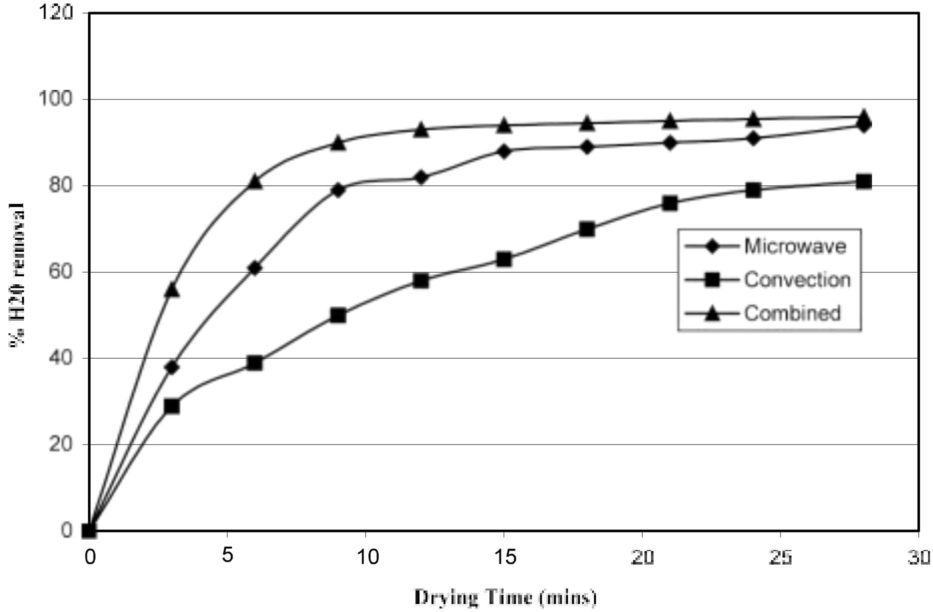

Fig. 2. Drying of dewatered sediment sludge's with microwaves (after Gan, 2000).

that any operation generating sludges containing oil, water and solids can potentially be treated. EPRI CMP, along with Carnegie Mellon Research Institute, USA, have funded several projects to evaluate the ability of microwaves to enhance the separation of oil-water sludges (EPRI CMP, 2001). Initial results have been very encouraging with separation using their process taking minutes as opposed to hours using conventional methods. Oil– water separations utilising microwaves were shown to require 90% less space, and the resulting product has some associated value.

Microwaves may be utilised in the processing of packaging wastes. Pyrolysis is an environment friendly disposal method for plastics whereby the hydrocarbon content of the polymers is recycled by thermal degradation. In particular, aluminium/plastic laminates have been investigated. This involved the pyrolysis of the waste in a bed of carbon that is heated by microwave radiation. The content of aluminium foil is recovered as very high quality aluminium, and the organic content is cracked to produce liquid and gas hydrocarbons (Ludlow-Palafox et al., 2001).

Another area where research is also being carried out is the sterilisation of hospital wastes. Hospital wastes (HW) produce an environmental problem due to the very large volumes produced each year. In Italy alone, the yearly production of HW is approximately 250 000 tonnes and only 60 000 tonnes are treated by incineration. Up to sixty percent of the waste produced could be landfilled if suitable sterilisation treatments are carried out (Tata and Beone, 1995).

A comparative study (Xia and Pickles, 2000) has been carried out to investigate any advantages that the microwave assisted caustic leaching of electric arc furnace dust (EAF) might have over conventional processes. Again, the driving force for this study was the large volume of the dust produced (700 000 tonnes per annum in USA), and the increasing restrictions on the landfilling of the waste product due to its leachate potential. Comparison showed that for the microwave assisted process, higher zinc recoveries (5 – 10%) were achieved in a tiny fraction of the time it took for the conventional process (again minutes as opposed to several hours).

Considerable amounts of research have been carried out on the potential recycling of tyres. Waste tyre processing can provide

S re-use of the rubber material (to produce products similar to the initial ones);
S recovery of materials and energy.

Due to the vulcanisation process in the manufacture of rubber, used tyres are not directly reusable. It is necessary to treat the rubber with a devulcanisation process for regeneration and reuse as virgin materials (Sharma et al., 1998). Devulcanisation breaks the sulphur–carbon bonding that makes rubber stable. Alternatively, tyres can be milled, either mechanically or cryogenically, to give an equally manageable granular material or powder. The milling process tends to be cheaper than the devulcanisation one.

However, with a microwave heating process the correct amount of energy can be used to cleave carbon–carbon bonds without depolymerisation occurring (Adhikari et al., 2000). The presence of polar compounds is a prerequisite for microwave devulcanisation to be effective. An example is sulphur vulcanised elastomers that contain such polar groups and are thus suitable for this method.

A pyrolysis plant that employs microwave energy to break down the tyres has been developed (Robinson, 1989). A carbon recovery of 36% is claimed, with the main product (33%) being the highly valued activated carbon the char product fraction. Other products include steel cord and hydrocarbon oils, while the remaining component— a mixture of hydrogen and methane gases— helps to power the heating process. As the process is carried out in a closed system (inert atmosphere—nitrogen), the production of dioxins, soot and ash is prevented.

2. Minerals processing with microwave energy

Various applications of microwave heating have been proposed for the processing of minerals. One particular area is the reduction of grinding costs through a phenomenon known as thermally assisted comminution. Thermally assisted comminution is the heating and quenching of ores to reduce lattice strength, therefore, reducing grinding costs. Conventional thermally assisted liberation of minerals requires large heat inputs and the overall energy balance is unfavourable (Veasey and Fitzgibbon, 1990). Microwave thermally assisted liberation has several attractions mainly that as only responsive phases within the material are heated, no energy is wasted 'bulk heating' the sample. In addition, there may be no need to heat the material to high temperatures (Kingman et al., 1999).

The main advantages of microwave heating in mineral processes are (Haque, 1999)

- non-contact heating;
- energy transfer, not heat transfer;
- rapid heating;
- material selective heating;
- volumetric heating;
- quick start-up and stopping;
- heating starts from interior of body;
- higher level of safety and automation.

An important application of microwaves in mineral processing is the inducement of thermo-mechanical stresses within the treated mineral to reduce grinding energy. Different minerals have different properties when placed in the energy field. These differences can be attributed to the differences between the conductivities of the minerals or their dielectric loss factors and bonding properties (Hua and Liu, 1996). It then follows that certain minerals within an ore may heat up faster than other minerals. These different heating rates in turn produce differing rates of expansion and the resulting thermo-mechanical stress can be enough to exceed the strength of the material being irradiated, thus cracking the ore. High temperatures may not necessarily be needed, as a differential thermal gradient should be enough to induce sufficient stresses within the material.

Microwave thermally assisted comminution is most effective when a microwave absorbing material is contained within a transparent gangue (Kingman et al., 1999). Fractures induced as a result of microwave heating a massive Norwegian ilmenite ore for 30 s at 2.6 kW and 2.45 GHz are shown in Fig. 3 (Kingman et al., 1998).

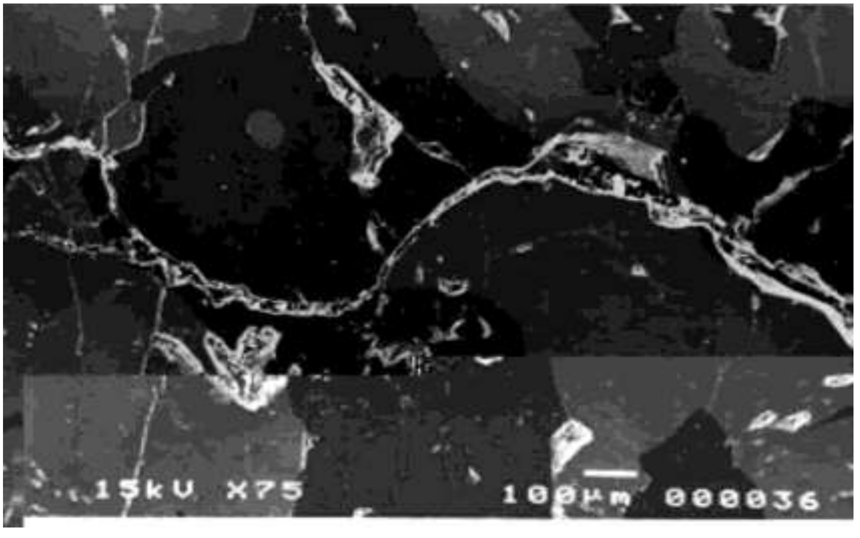

Fig. 3. Microwave induced fracture between different ore minerals (after Kingman et al., 1998). Treated 30 s at 2.6 kW, 2.45 GHz.

Table 1
Qualitative analysis of microwave heating of minerals (after Chen et al., 1984)

Mineral	Power (W)	Heating response
Arsenopyrite	80	Heats, some sparking
Bornite	20	Heats readily
Chalcopyrite	15	Heats readily, sulphur fumes
Covellite	100	Difficult to heat
Galena	30	Heats readily with arcing
Pyrite	30	Heats readily; emission of sulphur fumes
Pyrrohtite	50	Heats readily
Cassiterite	40	Heats readily
Hematite	50	Heats readily
Magnetite	30	Heats readily
Monazite	>150	Does not heat

These fractures are due to the differences in the expansion rates of the contained ore minerals. Examples of highly absorbing materials include metal oxides, carbon, metal halides, sulphide ores, arsenides, sulphosalts and sulphoarsenides (Walkiewicz et al., 1991). Examples of transparent minerals include the common gangue minerals, silicates, carbonates, sulphates and some oxides (Haque, 1999; Kingman et al., 1998; Salsman et al., 1996). Investigation into the influence of microwave radiation on mineral heating rate has been carried out with 40 minerals being exposed to varying power microwave radiation (Chen et al., 1984). The results of this qualitative study are summarised in Table 1. This study was extended several years later in a more quantitative manner when 135 reagent grade minerals and compounds were microwaved using a 1 kW, 2.45 GHz oven. The maximum temperature achieved for the samples and the time required to reach the temperature were recorded. The results of this study are summarised in Table 2 (Coss and Cha, 2000). It has been demonstrated that microwave energy has many potential applications in mineral treatment and metal recovery operations, these include heating, drying, carbothermic reduction of oxide minerals, leaching, roasting/smelting and pre-treatment of refractory gold ores and concentrates (Haque, 1999).

An important area of research into the application of microwave energy for minerals processing is in the regeneration of granular activated carbon in the carbon-in-pulp process (CIP). Modern gold-recovery techniques depend on the fact that gold (and silver) dissolve in dilute solutions of cyanide. The broken ore from the mine is first ground to a fine powder, and then the slurry of fine ore and water (the 'pulp') is treated with cyanide in large tanks that are stirred mechanically or by air-agitation. This material is filtered and then passed through a series of adsorption tanks. Pulp flows continually from the first vessel to the last in the series, and the carbon is transferred intermittently by pumping in the opposite (counter current) direction. In standard techniques the gold is eluted from the loaded carbon with a solution of cyanide and caustic soda, and then recovered by electrolysis or by precipitation with zinc dust. Laboratory scale tests have been completed on the application of microwave regeneration of the loaded carbon from the CIP process (Bradshaw et al., 1998). It has been found that regenerated carbon 'outperformed conventionally regenerated carbon' when reused in the CIP process. A preliminary economic assessment concluded that 'the capital cost for 120 kg/h microwave unit would be R540 000 (vUS$32 000 with an annual operating cost of R320 per tonne carbon (vUS$18 per tonne))' yielding a return on investment of 12%. Due to the high market value of gold there is sufficient financial scope for the additional energy cost of an industrial scale microwave regeneration unit (Van Wyk et al., 1997).

A significant body of work has been carried out on the microwave treatment of coal. Power generation consumes vast quantities of coal that requires prior-grinding/ comminution to facilitate complete combustion. Conventional heating of coal prior to grinding has been shown to increase its grindability and can save up to 40% of grinding energy (Lytle et al., 1992). However, it was concluded that the energy requirement for preheating was greater than the energy savings in improved grindability. Hence only through the utilisation of waste heat could preheating be economical. Subsequent work on the use of microwave radiation to dielectrically preheat coal, or rather the water present within the coal matrix (Marland et al., 2000) has shown reductions of up to 50% in the relative grindability of the various coals, after 5 min of exposure in a 650 W, 2.45 GHz oven. The reductions were 'believed' to be a combination of fracture mechanisms, inherent moisture within the coal structure changing phase under considerable pressure and differential expansion by gangue mineral components'. The authors stated that there was clear potential energy savings from the adoption of a microwave preheating process by the power generation industry. Fig. 4 shows the reduction in comparative work

Table 2
Microwave heating of minerals (after Walkiewicz et al., 1988)

Mineral	Maximum temp (°C)	Time (min)
Albite	69	7
Chalcocite	746	7
Chalcopyrite	920	1
Chromite	155	7
Cinnabar	144	8.5
Galena	956	7
Hematite	182	7
Magnetite	1258	2.75
Marble	74	4.25
Molybdenite	192	7
Orthoclase	67	7
Pyrite	1019	6.75
Pyrrohtite	586	1.75
Quartz	79	7
Sphalerite	88	7
Tetrahedrite	151	7
Zircon	52	7

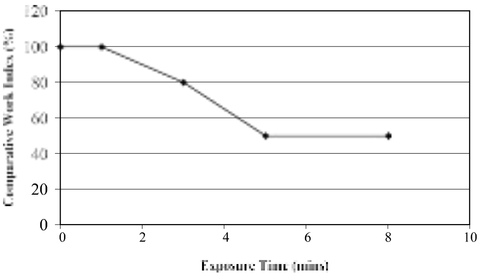

Fig. 4. Comparative work index vs. exposure time for typical coal (after Marland et al., 2000).

index with microwave exposure time for a typical coal treated at 650 W, 2.45 GHz for varying time periods.

Further work has been carried out to design apparatus for coal heating to produce metallurgical or blast furnace coke, however, no process information is available (Marland et al., 2000).

The possibility of reduction in sulphur levels in coals by the removal of elemental sulphur or pyrite has been identified (Agarwal et al., 1975) and it is suggested that removal rates of elemental sulphur could be improved through the application of microwave energy. At 2.45 GHz pyrite heats more rapidly than the coal, this heating has the effect of enhancing the magnetic susceptibility of the pyrite improving the removal rates by magnetic separation. Mossbauer analysis (Weng, 1993) of the evolution of pyrite present in raw coal after microwave irradiation concluded that pyrite decomposed according to the reaction.

$$FeS_2 \rightarrow Fe-(1-x)S \rightarrow FeS \qquad (0 < x \leq 0.125) \tag{1}$$

The reaction was found to progress from left to right as irradiation time increased. It was calculated that (Weng and Wang, 1992) the inorganic desulphurisation efficiencies for microwave treatment are 5 – 44% for irradiation times of 30 – 100 s. These efficiencies can be further increased to a 97% decrease in inorganic sulphur content in coal for a 100 s irradiation time when the process is combined with successive acid washing treatment (Weng and Wang, 1992). It has also been found that the rate of coal desulphurisation is improved by microwave irradiation in conjunction with a molten mixture of NaOH and KOH (Hayashi, 1990). Coal desulphurisation by reaction with hydroiodic acid (HI) in a sealed reactor in H_2 with microwave heating for 10 min, resulted in >99% pyrite sulphur removal and 64.7% removal of organic sulphur (Ferrando, 1996).

Another potential method that has been investigated is the use of microwave digestion to determine directly the forms of sulphur present in a specific coal (Laban and Atkin, 2000). This is useful for the selection of the optimal cleaning strategy for sulphur removal, for coal pulverisation and geological investigations of coal seams. An approach to desulphurisation has been suggested (Laban and Atkin, 2000) that combines microwave and gamma ray treatment for the simultaneous desulphurisation, demineralisation and comminution of high sulphur coals.

Many mineral processing applications have been tested only on a laboratory scale and the engineering realities of large-scale operations are yet to be fully realised. Of particular concern are the modest power outputs of industrial magnetrons relative to the power requirements in mineral processing operations, the high capital cost of microwave equipment and the poor penetration depth of microwaves. Review of these applications, and comparison to guidelines developed for successful microwave technology transfer, suggests that niche areas for microwave heating are in the processing of low-throughput concentrates, especially where volumetric heating leads to enhanced rates of energy transfer. A recent study concluded that in order to treat the large throughputs of most mineral processing industries (several 1000 – 30 000 tonnes per day), several generators may be needed to run in parallel, which may not offer a cost advantage over the conventional process (Haque, 1999). The highest microwave power generator available is 75 kW at 915 MHz. Larger power capabilities are required to deal with these large tonnages, which incur higher energy costs, energy efficiency of microwave generators is, therefore, an important factor. It is stated that (Haque, 1999) conversion efficiency from electrical energy ranges from 50% at 2450 MHz to 85% at 915 MHz. Microwave energy, therefore, compares unfavourably with conventional electrical heating in this respect.

Granulated actiuated carbon (GAC)

The main areas of application of microwave heating with respect to activated carbon are production, regeneration and treatment of compounds adsorbed onto the carbon matrix (Menendez et al., 1999a). Although the dielectric heating properties of microwaves are already being used in 'various technological and scientific fields' there are relatively few publications that describe the use of microwaves for heating carbon materials (Menendez et al., 1999a).

There are a number of specific advantages for the application of microwave heating to granular activated carbon, principally that GAC's absorb microwave energy quickly (Tai and Jou, 1999a). It has also been suggested that 'microwave treatment is less time consuming than conventional heating' with the associated reduction in inert gas consumption (Menendez et al., 1999b). Additionally, microwave furnaces are generally smaller than conventional furnaces. When compared with conventional electric tube heating (Menendez et al., 1999b) microwave heating was found to be an 'efficient and attractive way of removing oxygenated functionalities from carbon surfaces'. A schematic of the microwave apparatus used for this experimental programme is shown in Fig. 5 (Menendez et al., 1999b). Microwave treatment has also been found to produce comparable changes in the textural and chemical properties of the activated carbon but over a far shorter time period. A separate study undertaken concluded that microwave regeneration of activated carbon produced a product that performed better than standard regenerated carbon (Van Wyk et al., 1998).

Production of activated carbon involves two stages, i.e. pyrolysis and activation. Initially the carbonaceous materials are pyrolysised in an inert atmosphere at about 600 – 800 °C and then subsequently activated by exposure to partial gassification at temperatures of around 900 °C in the presence of oxidising gases. The main problems with this process are long process times (several days to as much as a week) (Guo and Lua, 2000) and the generation of a thermal gradient from the hearth walls through to the centre of the furnace. Microwave heating solves both of these problems by providing both internal and volumetric heating that allow the reaction to proceed more efficiently at lower bulk temperature. This results in energy savings and shortening of the process time.

NO_x gases adsorbed onto a char bed can be reduced to nitrogen and carbon oxides by the application of microwave energy, concurrently the char is regenerated for reuse (Cha and Kong, 1995). It has been found that the microwave induced regeneration of NO_x increased the surface area of the char from 82 – 800 m^2/g after nine cycles of adsorption and regeneration, increasing the adsorption capacity and hence the rate of adsorption (Kong and Cha, 1995). Additional work stated that the process is capable of reducing almost 90% of adsorbed NO_x (Kong and Cha, 1996). The authors of this study suggested that sites occupied by NO_x absorb more microwave energy than pure char. These sites consequently heat up rapidly and turn into hot spots, where the rapid reduction reactions take place. Furthermore, a higher percentage of HNO_3 in the feed gas results in a higher temperature of product gas; from this it was inferred that sites occupied by HNO_3 might absorb more microwave energy than those by NO_2. As much as 90% of the adsorbed NO_x was reduced in this regeneration process. A significant advantage of this method, as a consequence of rapid and efficient heating, is that the temperature of gases produced is close to room temperature. More recent work (Zang et al., 1997) reports that microwave reduction of NO_x can obtain reaction efficiencies of up to 98% when microwave energy is applied continuously.

Processes applying GAC adsorption and microwave decomposition to the treatment of VOCs have shown considerable savings in energy consumption and process efficiency (Tai and Jou, 1999b). An investigation into the microwave regeneration of activated carbon used to remove organic solvents, namely, methyl ethyl ketone (MEK), acetone and tetrachloroethylene (TCE) from air has been carried out (Coss and Cha, 2000). The adsorbed vapours were desorbed quickly in a microwave field and then recovered. The regenerated activated carbon was found to have the same surface area and adsorption capacity as the virgin GAC.

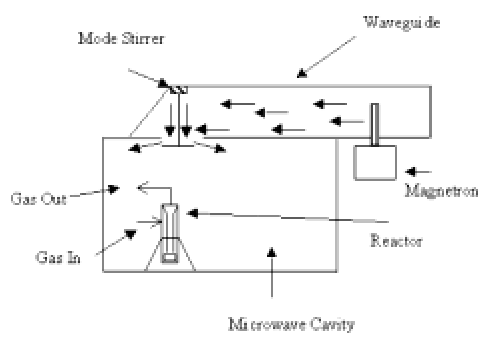

Fig. 5. Schematic of multimode resonant cavity microwave heater used for modification of the surface chemistry of active carbons (after Menendez et al., 1999b).

Progress towards industrial application has been improved significantly with the development of polymeric adsorbents (PAs). It has been stated that (Opperman and Brown, 1999) PAs have several advantages over GAC, namely that for comparable capture efficiencies PAs are semi-transparent to microwaves allowing microwave energy to be applied efficiently through the adsorbent bed. PAs are reactivated at much lower temperatures than GAC— <350 °C as opposed to >1400 °C. In addition, unlike GAC, PAs can adsorb reactive solvents (MEK, cyclohexanone and styrene) without catalysing their decomposition. PAs, being inherently hydrophobic, can also maintain high absorptive capacity in humid environments. Combined with a microwave application system and monitoring technology VOCs in a gas or liquid stream can be desorbed and condensed prior to reuse as a product or solvent resource

3. Conclusions

In the preparation of this article a significant number of references have been examined. Many have stated that the effective adoption of the microwave heating would possibly reduce process time and reduce the required process energy consumption. Apart from highly specialised applications microwave heating applications have seen little commercialisation in the field of environmental engineering. This is for several reasons. Firstly, little fundamental data exists regarding the dielectric properties of materials. The second reason for the lack of development of microwave heating processes is a lack of knowledge concerning the design of microwave heating equipment. Without knowledge of material dielectric properties efficient cavities (reducing the energy input) cannot be designed. Indeed, a detailed knowledge of microwave engineering is required before any process can be developed efficiently to a pilot or industrial scale. However, microwave assisted processes do not rely on benefits from reduced energy consumption alone other benefits include process timesavings, increased process yield and environmental compatibility. Processes where a number of these benefits are apparent may be considered to be likely candidates for further development.

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