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Scale-up and design of a continuous microwave treatment system for the processing of oil-contaminated drill cuttings

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ABSTRACT

A continuous microwave treatment system has been developed for the remediation of contaminated drill cuttings at pilot scale. Using the mechanisms of oil removal as a basis, a design was produced using electromagnetic simulations to find the optimum microwave applicator geometry which yielded the most favourable power density distribution. Bulk materials handling and process engineering principles were systematically integrated with the electromagnetic design to produce a system capable of treating 500 kg/h of material. The effects of the key design parameters are simulated, and a number of the simulations are verified with experimental data. It is shown that the environmental discharge threshold of 1% oil can be achieved in continuous operation, and the sensitivity of the system to changing feedstock properties is also highlighted. The parity between the simulations and experimental results in this paper highlights the necessity of electromagnetic modelling in the design and scale-up microwave processing equipment.

Keywords: Scale-up; Simulation; Microwave; Continuous; Drill cuttings

1. Introduction

Oil-contaminated drill cuttings arise from drilling activities in the exploration and extraction of oil and natural gas. The drilling of wells requires the use of 'drilling muds', which act to lubricate the drill bit, provide hydraulic power, maintain the stability of the well-bore and transport the drill cuttings back to the production platform (Okpokwasili and Nnubia, 1995). Drilling activities in mature fields generally require oil-based muds for deeper well sections, high-angle wells and poorly consolidated rock formations. The drill cuttings return to the production platform with the circulating drilling mud, where a primary separation is performed. The separated cuttings were, until recently, discharged straight into the sea without further treatment. Environmental legislation for the UK now stipulates that in order to discharge cuttings into the North Sea the residual oil levels must be <1% by weight (Oslo and Paris Commission, 2000). In contrast, the discharge limits in the Gulf of Mexico are 5% (US Environment Protection Agency, 2002). Typical North Sea cuttings samples produced using OBM contain around 15% oil, meaning that treatment is required before disposal. Recent landfill directives (Council Directive, 1999) and concerns about transporting cuttings to shore mean that an offshore treatment process is desirable, and microwave treatment was previously shown to be successful at laboratory scale (Shang et al., 2005, 2006; Robinson et al., 2008).

1.1. *Microwave heating*

In conventional thermal processing, energy is transferred to a material through conduction, convection and radiation. In contrast, microwave energy is delivered directly to materials through molecular interactions with the electric field component of the microwaves. The internal temperature distribution of a material subject to conventional heating is limited by its thermal conductivity, whereas microwave heating results in all individual elements of the material being

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heated individually and instantaneously. Consequently, heating times using microwaves can often be reduced to less than 1% of those required using conventional heating methods (Meredith, 1998).

There are three generic classifications for the behaviour of materials upon interaction with a microwave field:

1. Transparent (low dielectric loss materials) – microwaves pass through the material with little absorption
2. Opaque (conductors) – microwaves are reflected by the material and do not penetrate
3. Absorbing (high dielectric loss materials) – microwave energy is absorbed based on the electric field strength and the dielectric loss factor (Meredith, 1998).

Microwave processing has distinct advantages in the treatment of materials which contain a mixture of absorbers and transparent components. Microwave energy is absorbed by the substances with a high dielectric loss factor whilst passing through the low loss (transparent) material, resulting in selective heating. In this case, significant energy savings are possible since the dielectric material can be heated without heating the entire matrix. From Clark et al. (2000), the power absorbed per unit volume, or power density (*Pd*), is given by:

$$Pd = 2\pi f \varepsilon_0 \varepsilon'' |E|^2 \quad (1)$$

where *f* is the microwave frequency, ε_0 the permittivity of free space (8.85×10^{-12} F/m), ε'' is the dielectric loss factor and *E* the magnitude of the electric field (V/m). From Eq. (1) it is evident that the microwave energy absorbed by a dielectric material is proportional to the square of the electric field strength. The design of the microwave cavity is critical in that it can allow very well defined electric fields in a relatively small volume (single mode cavity), or can permit the electric fields to encompass a much larger volume, albeit with a compromise in the field definition (multimode cavity). The dielectric constant, ε', is also important in microwave processing, as it signifies the ability of a material to store electromagnetic energy. In contrast, the loss factor can be considered as the ability of the material to convert electromagnetic energy into heat. The dielectric constant is critical in determining the dimensions of the microwave structure used to process a material, as it determines the wavelength of the microwaves within the load.

1.2. *Key findings from previous work*

Previous microwave-based studies of drill cuttings treatment were carried out at small scales using single mode or multimode systems (Shang et al., 2006; Robinson et al., 2008). The main findings of these studies relate to the mechanisms of oil removal from the contaminated cuttings. Microwaves do not heat the oil directly as the oil is essentially transparent at microwave frequencies since it has a dielectric loss factor of 0.002 (Shang et al., 2005). Instead, the water within the pores of the cuttings is heated and converted to steam. As the steam escapes it physically entrains the oil, which exists at the surface of the cuttings fragments. Other potential mechanisms have also been identified such as stripping and steam distillation (Robinson et al., 2008), however the entrainment mechanism is the most thermodynamically attractive since energy only needs to be supplied to the water, and not to the surrounding rock fragments or oil.

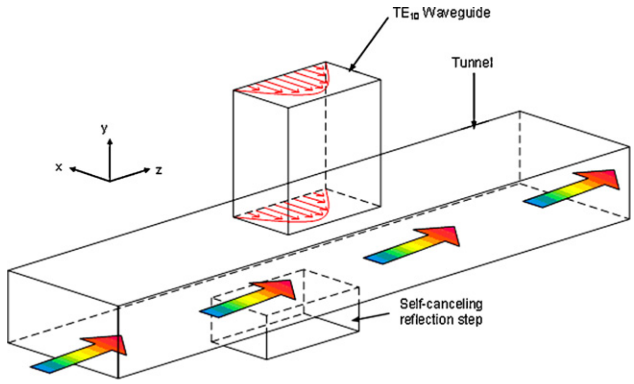

Fig. 1 – Diagram of a tunnel applicator.

To maintain the thermodynamic advantage of the microwave process, the water phase must be converted to steam before significant heat transfer takes place to the surrounding rock. To achieve this the heating rate ($\Delta T/\Delta t$) must be as high as possible, and the heating rate can be equated with the power density as shown by Eq. (2) (Shang et al., 2006):

$$\frac{\Delta T}{\Delta t} = \frac{Pd}{\rho C_p} \quad (2)$$

In moving from laboratory tests to a continuous treatment system, it is imperative that the power density is maximised to allow the rapid conversion of water to steam without significant heat loss to the surroundings.

1.3. *Scale-up to continuous system*

The need to maximise the power density eliminates multimode microwave cavities as viable scale-up options because of their inherently low peak power density and large power density distribution. Single mode cavities, whilst achieving very high peak power densities, yield an electric field distribution which falls to zero at the cavity walls because the tangential electric field must be zero at a metal wall. From Eq. (1), this means that the power density will vary between its peak value in the centre to zero at the edge of the cavity, meaning that the treatment will be sufficient in some areas but inadequate in other parts of the cavity. Not all components of the electric field equal zero at a metal wall, and other microwave cavity designs can be used to give more even electric fields. A solution which yields both high and even power densities across the cavity geometry is to utilise a tunnel applicator with a self-cancelling reflection step, and Figs. 1 and 2 illustrate this concept.

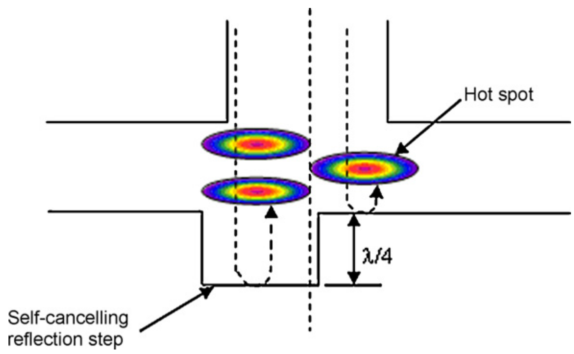

Fig. 2 – Effect of self-cancelling reflection step on the power density distribution.