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Remediation of oil-contaminated drill cuttings using continuous microwave heating

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ABSTRACT

This paper outlines a novel, continuous pilot-scale microwave treatment process for the remediation of oil-contaminated drill cuttings from North Sea drilling activities. The underlying scientific methodology is highlighted, and the development of the continuous processing concept is discussed. Continuous tests were carried out at throughputs up to 250 kg/h using microwave hardware capable of delivering up to 15 kW of microwave power at 2.45 GHz. It is shown that the cuttings can be remediated to below the offshore discharge threshold of 1% oil on cuttings, and that clean-up can occur to below 0.1% oil, which is the classification for non-hazardous waste. The trade-off between applied power, throughput and residual oil content is shown for tests carried out continuously over several hours. The energy consumption of the process is also shown in relation to the remediation levels achieved. The results obtained with the continuous pilot-scale system are compared with previous batch laboratory studies.

1. Introduction

Oil-contaminated drill cuttings arise from drilling activities in the exploration and extraction of oil and natural gas. Drilling fluids known as ‘muds’ are used to lubricate the drill bit, provide hydraulic power and transport the drill cuttings back to the production platform [1]. The separated cuttings were formerly discharged straight into the sea without further treatment, which lead to the degradation of the marine environment in the vicinity of the platform due to the hydrocarbon contamination. Environmental legislation for the UK now demands that oil levels must be <1% by weight for discharge to take place [2]. In contrast the discharge limits in the Gulf of Mexico are 5% [3]. Drill cuttings samples obtained from the North Sea, and produced using oil-based muds (OBM) can contain 5–15% oil, meaning that treatment is required before disposal. Recent landfill directives [4] and concerns about transporting cuttings to shore mean that an offshore treatment process is desirable, and microwave treatment has been identified as a candidate technology.

1.1. Previous studies of microwave heating

Along with our previous work in this area [5–7] there are several review articles and texts which introduce the concepts of microwave heating, for example [8,9], so the basics will not be discussed in detail here. There are two principal advantages of microwave heating in process engineering applications:

1. Selective heating, meaning that energy does not have to be wasted bulk-heating an entire material volume.
2. Volumetric heating, meaning that energy can be dissipated instantaneously beyond the surface of a material, overcoming heat transfer limitations.

Selective heating accounts for the energy efficiency of many microwave processes compared with conventional heating. Volumetric heating can result in very fast heating times, leading to compact equipment with high material throughputs and low residence times.

Previous microwave-based studies of drill cuttings treatment were carried out at small scales using single mode or multimode systems [5,7–9]. 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 [6]. 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 [7], however the entrainment mechanism is the most thermodynamically attractive since energy

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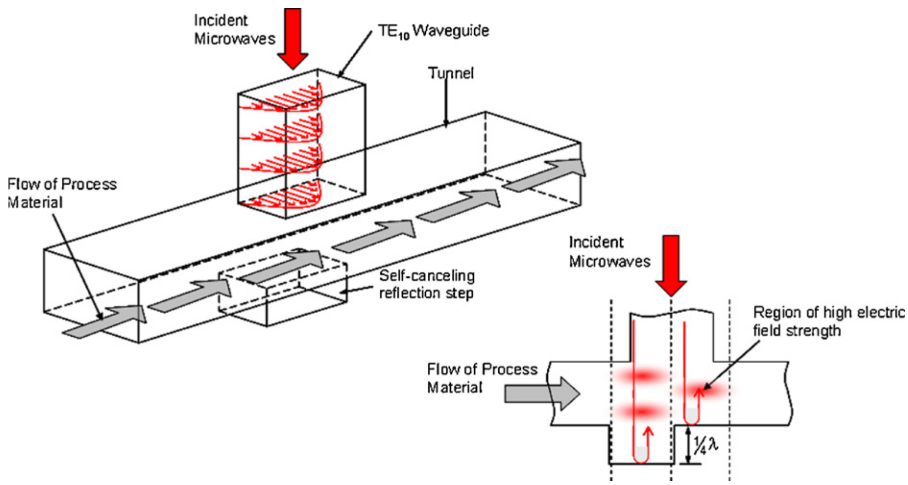

Fig. 1. Concept of a transverse E-field applicator.

only needs to be supplied to the water, and not to the surrounding rock fragments or oil.

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. (1) [5]:

$$\frac{\Delta T}{\Delta t} = \frac{Pd}{\rho C_p} \quad (1)$$

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. The requirement for a high power density leads to a corresponding requirement for a high-strength electric field, which in turn dictates the type of microwave cavity which is used.

1.2. Microwave cavities for continuous processing

Despite the high power densities obtainable, single mode cavities cannot be used for the vast majority of industrial applications because of their relatively small volume and the inherent non-uniformity of the electric field. A more useful concept for industrial applications which still allows high power densities is the transverse travelling wave applicator, which is an applicator falling into the category of broadband non-resonant devices. An example of such a system is a transverse E-field applicator with a self-cancelling reflection step, and this is shown in Fig. 1.

The process material is conveyed through a tunnel of rectangular cross-section, and the microwaves are fed orthogonally to the direction of the feed. A reflection step is used at the base of the cavity to offset the reflection, producing three overlapping regions of high power density. The variation in power density is largely overcome by the overlap of the three hot spots, so process material will experience a region of high power density irrespective of its vertical position. The orthogonal feed of the waveguide means that the power density is uniform across the width of the cavity also. Transverse E-field applicators yield a high power density and a power density distribution which is relatively even across both the width and height of the cavity.

This is the first study that reports a continuous microwave treatment system for the removal of oil from drill cuttings.

2. Experimental and materials

The cavity used for this work is shown in Fig. 2.

The applicator was designed so that it could be assembled around a rectangular-troughed conveyor belt. It was constructed from aluminium in two sections, which when assembled around the conveyor formed the cavity in the centre, with a choking section on either side. The purpose of the chokes is to stop microwaves propagating out of the cavity into the surrounding environment. The cavity was integrated into a pilot-scale testing facility as shown in Fig. 3.

The continuous pilot-scale system consists of a 5–30 kW variable power microwave generator, which delivers microwaves at 2.45 GHz to the cavity via several sections of WR430 waveguide and an automatic E–H tuner. The tuner works by varying the geometry in the E and H planes to match the impedance of the microwaves with that of the cavity, with an algorithm used to vary the geometry so as to minimise the reflected power. Any reflected power is absorbed in the circulator, which uses a cold water load, and this protects the magnetron and power supply from excessive returned microwave energy. A stream of cold nitrogen was introduced at 5 l/min down the waveguide entrance to the cavity, which was done to provide a positive pressure and prevent oil and water vapours from passing through the waveguide to the microwave generator.

The drill cuttings are fed from a feed hopper into a twin shaft mixer, where dry material could be introduced to control the moisture content of the feed to the microwave cavity. The mixer deposits the cuttings onto a conveyor belt, which was made from woven Nomex fibres, and formed into a trough to contain the process material. A heated nitrogen stream at 50 l/min was introduced at the material feed to act as a sweep gas, and also to provide an

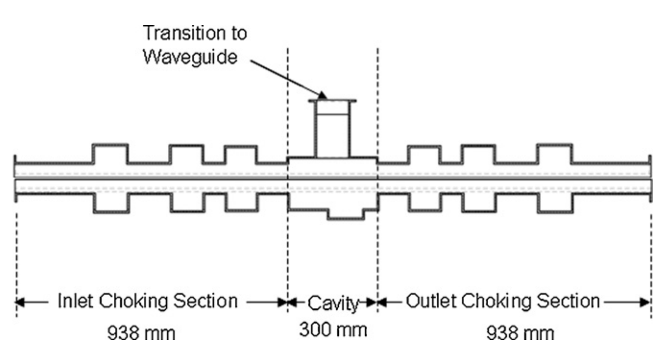

Fig. 2. Transverse E-field microwave applicator with self-cancelling reflection step.