Chemical Engineering Research and Design 139 (2018) 34–38

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Integration of Time Domain Reflectometry in a smouldering reactor

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ARTICLE INFO

Article history:
Received 17 April 2018
Received in revised form 20 August 2018
Accepted 9 September 2018
Available online 19 September 2018

Keywords:
Smouldering combustion
Time Domain Reflectometry
Waste treatment
Integration

ABSTRACT

Self-sustaining smouldering is a novel technology that has been efficiently applied for soil remediation and the treatment of waste at very high moisture content. During smouldering, combustion of an organic phase occurs within an inert porous matrix. Simultaneously, processes such as evaporation, condensation and further migration of water take place. Due to the dynamics of the smouldering, all these processes are interconnected. Water evaporation and re-condensation is one of the main mechanisms responsible for smouldering quenching. The understanding of water migration within the porous medium is crucial for the design and development of self-sustaining smouldering reaction systems. This paper introduces the first smouldering reactor performing Time Domain Reflectometry (TDR) measurements during smouldering combustion experiments, aiming to measure water content distributions within the porous matrix. An existing smouldering reactor is transformed into a coaxial transmission line designed for the propagation of electromagnetic signals. Wet artificial faeces mixed with sand were used for the tests, as its behaviour in smouldering was extensively studied. TDR signals and temperatures at different positions along the reactor were recorded simultaneously. This allows for the determination of the temporal changes of the water content distribution within the smouldering reactor. This development is the first step towards the determination of moisture content profiles during waste smouldering treatment applications.

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1. Introduction

Smouldering combustion is a slow, low-temperature, flameless form of combustion sustained by the heat evolved when oxygen reacts with the surface of a condensed phase fuel. Smouldering occurs in porous media, like in a burning cigar (Rein, 2009). Smouldering combustion has been demonstrated as an effective and efficient method for the treatment of waste with high water content (Rashwan et al., 2016; Yermán et al., 2017a, 2016, 2015).

High energy-efficiency is the key of this process, which allows treatment of waste with high water content in a self-sustaining manner. This means that after ignition, no energy is required and the combustion propagates through the material.

Smouldering requires that a fuel is porous, as this promotes a high surface area for heat and mass transfer, insulates the reaction front to reduce heat losses, and allows the flow of oxygen to the reaction zone (Pironi et al., 2009). By mixing the waste with an inert granular material, a porous matrix is created, with the necessary heat retention and air permeability properties for smouldering. Sand is commonly used because it has previously been identified as an effective agent for smouldering treatments (Pironi et al., 2009). Smouldering has also been extensively used for soil remediation (Scholes et al., 2015; Switzer et al., 2014, 2009), where the soil and contaminant, air, and groundwater coexist in the smouldering matrix.

Research on smouldering combustion lacks diagnostic methods, and usually does not go beyond temperature profiles and chemical

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https://doi.org/10.1016/j.cherd.2018.09.018
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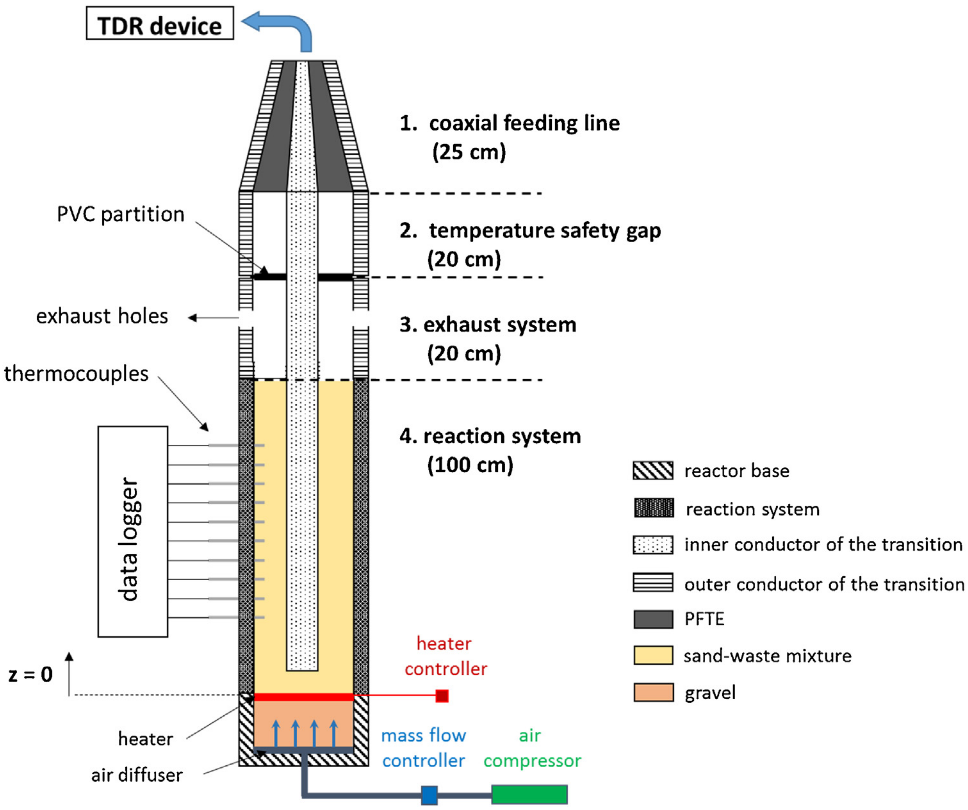

Fig. 1 – Schematic representation of the smouldering reactor transformed into a coaxial cell.

analyses. To the authors' knowledge, the work of Tse et al. is the only example using high-level diagnostics for smouldering applications (Tse et al., 1999). However, this uses is a dry material and therefore there is no study of water migration. For waste applications, the downward migration of water due to increased hydrostatic pressure when water condenses, enables a critical condition that quenches the reaction (Yermán et al., 2015).

The effect of moisture content on smouldering has never been systematically addressed, due to the lack of suitable observation methods. The advancement of innovative methods that can determine the temporal changes in moisture content distribution within a porous media, where concentrations and temperatures are changing, can shed light on the phenomena involved during smouldering.

Time Domain Reflectometry (TDR) is an acknowledged method for determining the water content of porous media (Robinson et al., 2003). The TDR method can monitor changes in water content and density in porous media by taking advantage of the dipolar character of the water molecules, which results in a high permittivity compared to other phases.

A TDR device measures the propagation velocity of a step pulse voltage along a transmission line: the velocity of this signal is a function of the effective permittivity of the material through which it travels. Conventional TDR technology is restricted to the point-wise determination of soil moisture, or mean water content, along with a TDR probe with a typical length of 10–30 cm. Recent developments have focused on Spatial Time Domain Reflectometry (STDR), which seeks the determination of water content profiles (Schlaeger, 2005). This approach requires inversion algorithms of the wave propagation along a transmission line due to an incident voltage step. The use of STDR for observing changes in water content during the smouldering process could optimise the application of this emerging technology, and even trigger new applications in the relevant industry.

This paper introduces, for the first time, an innovative prototype of a smouldering process applying STDR method. A smouldering reactor is transformed into a coaxial line that allows the propagation of electromagnetic signals. A proof-of-concept to simultaneously measure temperatures and TDR signals is presented, essential for understanding water migration and smouldering quenching mechanisms.

2. Materials and methods

2.1. Materials

The material selected for these tests is a well-characterized (Yermán et al., 2016, 2015) artificial faeces recipe, which has been extensively studied in smouldering applications (Yermán et al., 2017b, 2017a, 2015). The electromagnetic properties, and a dielectric spectroscopy for smouldering applications, were studied in Bore et al. (2016). A fresh batch of surrogate faeces is prepared prior to each test and mixed with sand (0.6–1.2 mm, 1700 kg/m^3 bulk density). A pre-existing upwards forward smouldering combustion column (Yermán et al., 2017b, 2017a, 2015) with an inside diameter of 16.0 cm is shown in Fig. 1.

The design requires a transition section that enables the "injection" of an electromagnetic wave into the reactor. This transition has three different coaxial line sections. From top to bottom, the first section (1) is made from a commercial connector, and consists of a 50 Ω conical transition filled with a low loss dielectric material (PTFE) providing the transition from the connector (N-type) to the dimension of the reactor. The second section (2) is a safety gap to protect the connector from potential high gas temperatures. Second and third sections are separated by a partition made of PVC. Section (3) is the exhaust system, where combustion gases leave the reactor through a set of holes. Section (4) is where the smouldering reaction and water migration take place. This section holds 10 horizontal thermocouples (TC) at different heights. A data logger (Agilent/HP 34980A) records the temperature from the TCs. The first TC (TC1) is located at 2 cm from the heater and is used to control the ignition of the medium (Yermán et al., 2015). It is worth noting that this system (i.e. the coaxial feeding line, transition, and reactor) represents a large one-port

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